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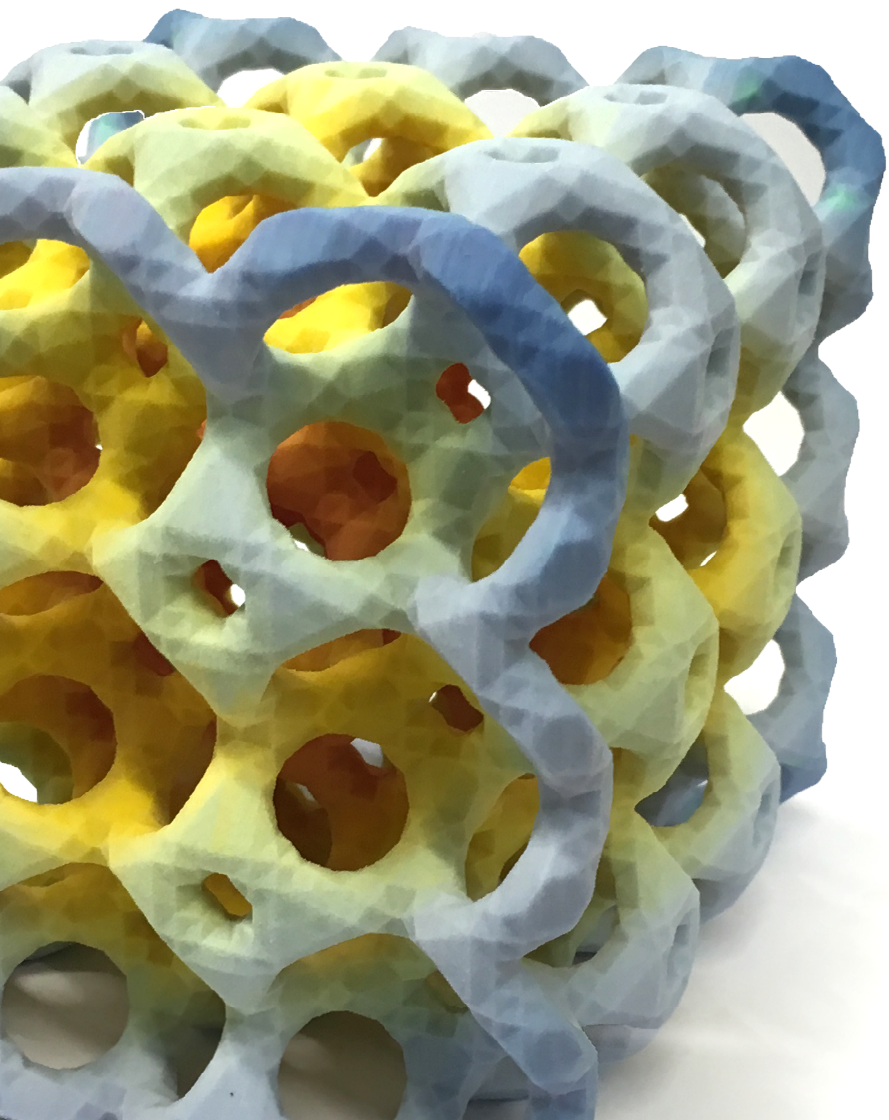
ASSESSING THE APPROPRIATENESS OF ADDITIVE MANUFACTURING

Development of a knowledge based assessment methodology to determine appropriateness of additive manufacturing for an organisation

Master Thesis
Industrial design engineering

Ing. W. van der Haar



TITLE PAGE

Assessing the appropriateness of additive manufacturing

Development of a knowledge based assessment methodology to determine appropriateness of additive manufacturing for an organisation

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ABSTRACT

Additive manufacturing (AM) is an upcoming technology that according to experts will The hype around Additive manufacturing (AM) has caused major interest of companies in a diverse range of sectors. Currently, many companies are evaluating the possibilities of using this upcoming manufacturing technology but do not have a clear overview of the impact and possibilities. Companies are not able to translate them into tangible outcomes because they do not have the knowledge or mindset to find appropriate solutions that solves their problems. However, organisations cannot afford to lean backwards, if so they might miss out and do not recognise possible AM benefits that create competitive advantage.

Capgemini is currently exploring how upcoming technologies like AM should be applied to gain competitive advantage for their clients. To reach this goal they collaborate with clients and offer them insight and create awareness to use this technology in a targeted manner. In order to enhance this process this research aims to develop an assessment methodology which is supported by a DSS to enable people with little knowledge of AM to ask questions and provide relevant information in each stage of the decision making process to determine the applicability of AM and indicate the value for further research into these areas.

The developed assessment is suitable for a diverse range of users with different backgrounds. Through the division in multiple levels the tool gradually build up the depth of knowledge and the required user input.

1. Level 1: Set baseline of knowledge and identify primary business focus
2. Level 2: Define depth of study and perform part selection
3. Level 3: Identify technical manufacturing alternatives
4. Level 4: Identify and develop possible future economic scenarios
5. Level 5: Summarize decision process and define next steps.

In the first level the process starts with constructing a knowledge baseline of AM. The basic principles are explained and differences are compared with traditional manufacturing technologies to indicate how and when AM can be applied as a manufacturing technology. In the following step the decision maker has to select a primary business focus to define the goal for the assessment. The second level defines the depth of study before proceeding and is followed by a high level part selection where potential parts from a product portfolio are identified which might be suitable for further investigation. The most promising part is used in the third level where suitable production technologies are identified with an algorithm. This algorithm can identify AM processes but also includes traditional technologies and post processing steps. With this information the high level economics can be considered in the fourth level. In this stage decision makers can analyse future scenarios by reviewing different cost drivers. Finally, the assessment methodology is summarized in the fifth level. This level serves as a recap on the decision process and as brief for the engineering department.

Keywords: additive manufacturing, decision support systems, part selection, process selection, technical feasibility analysis

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Wouter van der Haar,
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LIST OF ABBREVIATIONS

AM	Additive manufacturing
AIE	Applied innovation Exchange
DfAM	Design for additive manufacturing
CAD	Computer Aided Design
DFM	Design for manufacturing
DSS	Decision support systems
IM	Injection moulding
NIST	National institute of standards and technology (America)
ASTM	American Society for Testing and Materials

1. INTRODUCTION

Due to the media hype around 3D printing, also known as additive manufacturing (AM), it seems that an increasing amount of companies are considering this technology. Many of those organisations are evaluating the use and impact of AM. They are afraid to miss big opportunities that may rise from AM and competitors may realise competitive advantage sooner.
In the first chapter an introduction of the initial position, focus definition of the thesis as well as the structure is presented. This chapter aims to provide easy access into this topic for the reader, outlines the goals and motivation for Capgemini and describes the problem definition of the research. The introduction starts with a brief description of the context of the organisation in which the graduation project is executed. Then the limitations and boundaries will be defined in the scope which forms the basis to define the research questions.

1.1. Capgemini and the Applied Innovation Exchange

The Applied Innovation Exchange (AIE) at Capgemini is an international network of labs sharing demonstrations, knowledge, and learning's. This initiative is focussed on exploring emerging technologies like 3D printing, virtual reality, Internet of Things and robots and aims at translating these into practical business cases. Each lab works in multi-disciplinary teams with profound sector expertise including designers, architects, entrepreneurs, data scientists and technologists. The labs provide clients of Capgemini insight into the possibilities of technological developments. The initiative is introduced to support the innovative focus of Capgemini. The global network of labs provides an ecosystem which brings together different partners, incubators, start-ups and academia to accelerate innovation.

As an IT/ICT company Capgemini positions themselves as market leader in technology, outsourcing and consultancy mostly in IT/ICT related projects. Clients expect that Capgemini is well informed about emerging technologies and how these developments might affect them because they believe this knowledge is needed in future projects. Therefore, it is important for Capgemini to stay on top of all new ongoing technological developments which have the potential to change industries. Through the AIE, clients are able to understand and apply emerging technologies. The Lab aims at helping the sales team convert ideas from the client into business for Capgemini. In the AIE Lab the innovative character of Capgemini is displayed to clients and in the AIE Studio, clients see what is possible and how technology can help them cope with innovative challenges.

The clients of Capgemini are large companies in a diverse range of sectors, from financial services and banking to aerospace and automotive. Visitors of the AIE are executives and department managers whom are interested in applying innovations to improve their business. AIE enables clients to plan for various technology and business shifts which are confronting their business on a daily basis. Clients approach Capgemini with questions that can be categorized in three perspectives (Westerman, Bonnet, & McAfee, 2014). 1) How can we improve the customer offerings and create more revenue by improving the products, 2) how can we improve our processes more efficient and reduce the involved time or costs and 3) What new business models might apply to us to create revenue in a new way.

1.2. Motivation for an additive manufacturing project

Clients expect that Capgemini has knowledge from emerging technologies like AM because often they are a partner in their technological and business developments. Clients notice changes in their industries and raise questions about these emerging developments. Organisations cannot afford to lean backwards because they might not recognise of the possible AM benefits to create competitive advantage. In a future where integrated digital technologies like AM become a part of the value chain, organisation should start assessing the readiness and appropriateness for integrating AM in their production processes (D. Cohen, George, & Shaw, 2015). In order to accomplish this, organisations have to find external partners that have expertise in this field.

One of the reasons for Capgemini to start investigating the field of AM are the increasing customer interest in the newest technological developments and strategic opportunities of AM. Because Capgemini is active in many industries and AM is applicable in most industries, investing in AM knowledge and practical lessons learned is relevant. This knowledge should give them expertise and insight in the AM technology to create awareness and inspire organisations to use AM. Capgemini believes that the technology has the power to change and influence industries. Offering their clients insight in the possibilities of a targeted use of AM and the advantage that can be gained when using this technology. The goal is that Capgemini consultants become experienced in identifying the appropriate opportunities and together with organisations they are able to assess the impacts of using AM. Ultimately, knowledge of AM technology is required to enhance current service offerings for example during operational excellence projects. At the moment, consultants obtain their information from the media which is often misinterpreted. Managing these expectations is important because the expectations raised in the media are often too high or too low.

Furthermore, Capgemini is focussed to grow from a technology partner to a strategic partner. Capgemini wants to be more involved in the strategic business compared to only focus on the implementation of IT/ICT technology. This should result in more agreement between the developed business solutions. When AM is applied in a strategic manner, the technology can be used in an optimal way. In the future Capgemini should be able to assist clients in the first steps of defining the strategic process for implementing AM.

This research is the first step for Capgemini in the field of AM and a general understanding of the technology has to be created. In order to enable clients to make strategic decisions whether AM is a relevant technology, awareness has to be created at the highest level of managers. Creating awareness requires a good understanding of AM technology and all its dependencies. Only creating awareness is not sufficient, clients should be able to find applications aiming to incorporate the advantages of AM. Clients have desire to know how to use AM and what the possible implications are. There is no consensus about AM applications due to the specific applicability of solutions which makes these assessments more complex (Jones, 2015). One solution might work in one industry does not ensure the same result in a different context.

The project aims at general-, business development-, operations-, production-, and R&D managers, who are interested in AM and considering to incorporate in their business but do not possess the knowledge to assess the opportunities. Important characteristics of the target group is the large difference in backgrounds and the different levels of understanding of manufacturing technology in general.

1.3. Problem definition

According to research, more than 60% of the companies are currently using or evaluating AM (Maddox, 2014). Most of the uses for AM is the production of prototypes and other visual models, but the technology becomes feasible to produce end-use parts (Gooch, 2013). Capgemini is willing to give visitors of the AIE insight in emerging technologies such as AM that have the possibility to disrupt markets however consultants do not possess the knowledge required for these assessments.

One of the major factors holding back the adoption of AM is the attitude and knowledge towards the process (Wohlers, 2014). Organisations are unfamiliar with the benefits of AM, and they are not aware of the applicability. Additionally, they are not informed about the differences in trade-offs when considering AM. Overall, the implications of AM on the organisation in terms of supply chain, processes, products, costs and time are unknown.

In literature, researchers show a bias towards traditional manufacturing (Kerwien, Collings, Liou, & Bytnar, 2013). Compared to conventional manufacturing there are differences in mindset that needs to change when assessing the value of AM (Sniderman, Monahan, & Forsythe, 2016). With traditional manufacturing the focus is on producing simple products in high quantities which are highly constrained by the production process. Assessing AM with this mindset and a lack of knowledge, causes a bias towards current manufacturing methods which makes it impossible to make a fair assessment between manufacturing technologies. Currently, the AM process is immature and not yet fully developed to meet customer demands, therefore most organisation still focuses on conventional production methods. Being informed of the newest developments in the field of AM is hard because the fields is fast changing and applications are industry specific (Jones, 2015). Knowledge of the new materials and AM parts properties, process parameters and overall performances will result in a greater understanding (Kerwien et al., 2013).

Some researchers describe the need to assess the suitability of AM before application (Doubrovski, Verlinden, & Geraedts, 2011). They also mention that a need is present for methods that give guidance how to benefit from the opportunities that AM offers. Identifying the possible AM applications is important in supporting the considerations of organisations for the use of AM compared to other manufacturing methods. Finding feasible solutions that will give organisations a competitive advantage is hard because of the traditional attitude towards product development decisions (Wohlers, 2014).
Frazier (2014) performed a literature review in which the need for a business case assessment for the adoption of AM as a full production technology is identified. In addition to that, according to a publication of NIST (National institute of standards and technology) the cost aspects of those business cases need to be considered to identify the potential applications that are specifically suited for this manufacturing technology (Thomas & Gilbert, 2014). Performing a cost benefit analysis gives insight in specific opportunities for a company. The need for guidance in the efforts of assessing the applications of AM technology is desirable (Mellor, 2014).

To solve this problem the development of an assessment methodology is proposed. The methodology should provide insight in the capabilities and limitations of the technology. With this knowledge organisations will be able to assess in the early stages the applicability of AM for their company and define business cases more efficiently.

1.4. Research Scope

Based on the need of Capgemini for AM knowledge they want to provide their clients with the latest insight in the opportunities or limitations of the technology. The need for a methodology that can assists in the process to assess the possibilities of AM should be specific to the context of organisations. Selection procedures for assessing the appropriateness of AM involves many criteria that often conflicts with the priorities which makes the procedure harder. Companies must be supported in the decision making processes to select appropriate applications for AM. On top of that, the selection of AM is not only limited to one process, alternative production technologies should be incorporated. This requires knowledge that is currently not available to consultants of Capgemini. Assessing the appropriateness of AM consists of many factors and there is no well understood or agreed upon procedure to reach the solution. Assessments require judgement and insight in the problem from the decision maker and due to this complexity these decisions are unstructured. Therefore the methodology should be supported by a decision support system (DSS) that can give advice on the basis of a database with knowledge. The DSS helps Capgemini consultants structure the assessment process and provides the clients with relevant knowledge and questions to assess the appropriateness of AM.

The scope of this research is to develop a methodology that helps consultants of Capgemini and clients better understand the capabilities of AM which enables identification of appropriate business cases. The objective of this research is to develop an assessment methodology that is supported by a DSS which gives insight in AM use cases and contains the knowledge required to assess the appropriateness of AM opportunities. The methodology should provide clients with awareness to identify suitable applications for AM. Based on the comparison with different production technologies the best manufacturing alternative can be selected. Not all production methodologies will be incorporated but the focus will be on CNC machining, casting for metals and injection moulding for plastics. Other production technologies and materials are out of scope of this research. After the assessment process, clients should have insight in the consequences and impact of AM in terms of technical (quality and performance) feasibility and economic considerations.

Developing such systems can be done from multiple perspectives, for example from a supply chain perspective includes the impact of AM on the whole supply chain and the operational management perspective focuses on the required prerequisites before implementing AM in an organisation. The focus of this thesis will be from a technical point of view which includes the technical feasibility and the economic considerations that are involved in AM. In order to fulfil the future demand of AM knowledge, the tool has to be flexible in adjusting the technical specifications to make assumptions. The characteristic the methodology should obtain are shown in Figure 1.1.

Provide knowledge

- Transfer AM principles, capabilities and the consideration factors,
- Provide insights by assiting in the exploration of the AM possibilities to identify strategic opportunities,
- Create awareness of the AM opportunities and differences with traditional manufacturing

Determine appropriateness

- Assess the opportunities of AM, and investigate if it is appropriate and how the organisation can benefit from the AM technology,
- Convert opportunities from ideas to business cases which requires a careful considerations of the technical feasibility and possible economic considerations

Understand impact

- Clients should be able to assess the impact of AM on the products and the product development process. The system should provide the implication and consequences of the choices.
- Possible future scenarios should assist decisionmakers to cope with possible future developments.

Figure 1.1. Characteristics of the methodology

On major contradiction is that Capgemini is an IT consulting company and does not have extensive engineering knowledge and does not wish to enter these paths. Additionally, Capgemini does not have experience in the field of AM technologies, some in manufacturing consulting services are offered but these are IT related. This research will provide a rather general overview of the possibilities and impact, it will not dive into detail about the specifics engineering of parts. Furthermore, this project does not focus on the impact of AM on the supply chain or organisations. Although these aspects are important in the consideration for a production methodology currently the technical factors are the most important because these define the limits what is currently technically feasible. Due to diversity of clients and industries, economic feasibility calculations lay outside the scope of this research.

1.5. Research questions

The problem definition and the scope outlined in the previous paragraphs, has led to the different research questions. The main question is divided in several sub questions and serve as guidance throughout this research. The main objective of this thesis is to:

> *Develop an assessment methodology which is supported by a DSS to enable people with little knowledge of AM to present relevant information in each stage of the decision making process to determine the applicability of AM and indicate the value for further research into these areas.*

The result of this research should show how the methodology works and what knowledge is relevant at which stage in the decision making process. Determining appropriate business cases should be approached by first presenting structured AM knowledge to obtain a common understanding. Clients who visit the AIE do have generally wrong expectations of the AM technology therefore a common understanding is required. With knowledge of AM, organisations are better able to determine appropriate opportunities specific to their organisation.

Main research question:

> *How can consultants with little AM knowledge efficiently assess possible AM applications for clients to determine appropriate business cases?*

In order to answer this question, the following sub questions are used to narrow the scope of the assessment methodology:

Sub questions:

1. What knowledge is required to realise a common understanding among decision makers in order to assess the use of AM efficiently?
2. How to compare the capabilities of AM with other (traditional) manufacturing methods?
3. What knowledge should the DSS contain and how should this be structured to ask relevant questions in each stage in the decision process?
4. To what extend are existing methods able to identify appropriate business cases for AM?
5. How can appropriate business cases that use the benefits and capabilities of AM be identified?
6. How to assess the possible impact of AM on the product in terms of technical performance and economic considerations?

1.6. Thesis outline

In this section an outline of the research is presented. The thesis consists of six chapters and the structure is visualised in Figure 1.2.

First, a literature review of the AM technology, the advantages and challenges in the application domain are presented. Furthermore, appropriate DSS variants and elements have to be investigated. The literature review analysis assessment methodologies which are already available. In chapter three, the theoretical development of the assessment methodology is described. Information obtained in the literature review will provide the general structure for the methodology. In chapter four the model is developed into a prototype that enables validation of the model in chapter five. In the last chapter, six, the all the research findings are concluded and recommendations are drawn for further research.

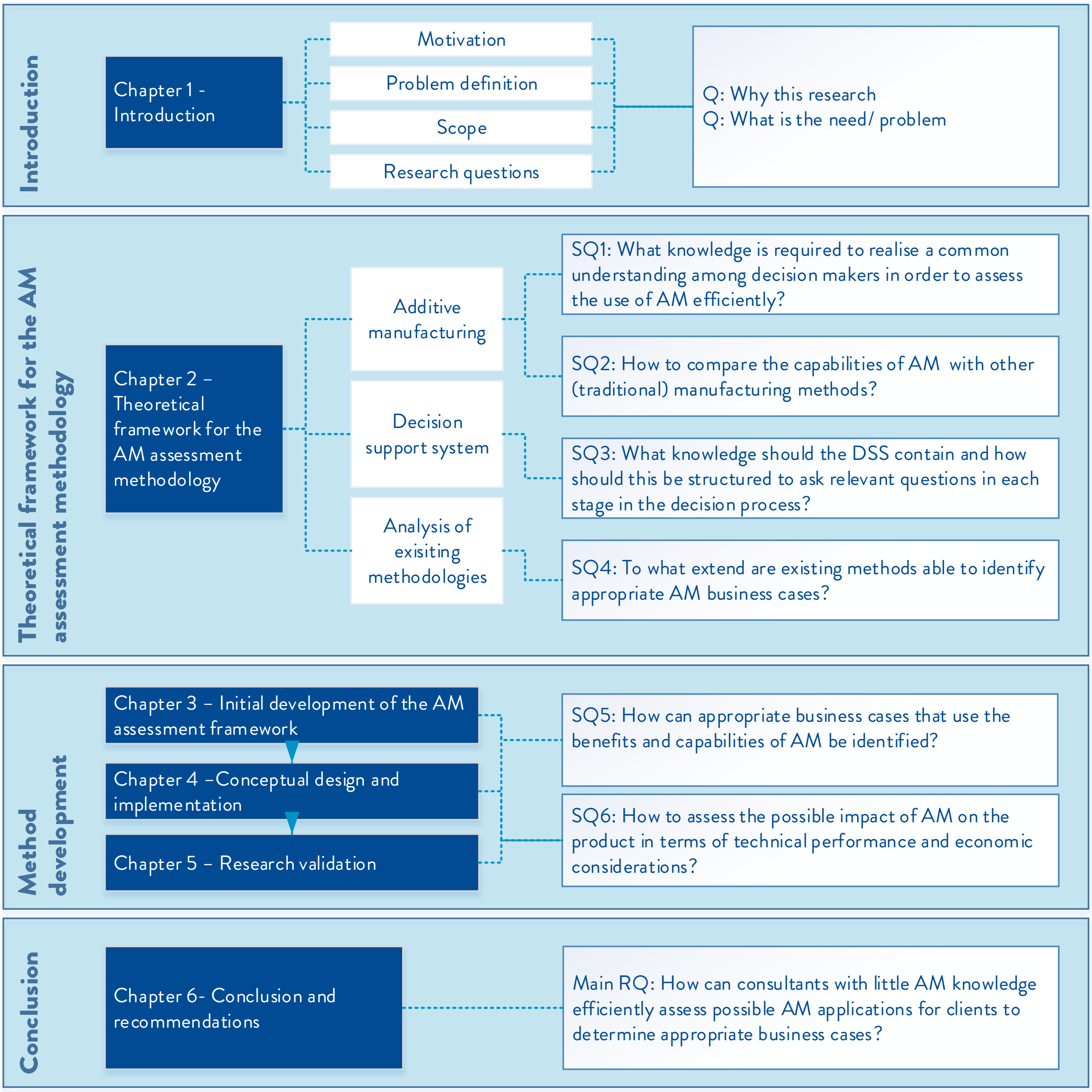


Figure 1.2. Overview of chapters in the thesis

1.7. Conclusion

More than 60% of the companies are evaluating AM. One of the most critical aspects of the industrial application of AM is how companies can use it as a manufacturing method for end-use products. The technology is not a replacement for the current conventional manufacturing methods because AM has special characteristics which can be exploited. The technical capabilities are growing which enhances these special characteristics. Unfortunately, companies still apply traditional considerations upon the decision to use AM (Wohlers, 2014). This creates a gap between the possibilities AM technology offers and where the technology it is used at this moment. A shift in mind-set is needed to make full use of the new possibilities that are not always directly visible. Specific AM knowledge is required to obtain such mindset. To make full use of the possibilities of AM, organisations should be aware of the capabilities that AM possess. The decision for AM is complex and specific knowledge is needed. Due to the high interrelation between the product characteristics and the process, knowledge of the effects when using AM in the production of end products is required.

In order to help business obtain knowledge of the possibilities that AM offers, research is needed to provide an overview how AM could improve the current business situation. Doing research in advance, results in insights of important challenges, implications and the potential of using AM systems in the future.

In the AIE there should be a method that can be used by multiple people to explain the benefits and capabilities of AM to a variety of clients. The aim of this research is to develop an assessment methodology for clients who visit the AIE and are interested in using AM in their processes or in some parts of their product portfolio. Such a methodology should structure the process where consultants of Capgemini create awareness among visitors through determining the applicability and identifying the possible applications of AM specific for their organisation. This research focusses on enabling clients to make informed decision by showing the possibilities of AM and provide insight in the consideration factors. Helping companies obtain insight into these factors should be integrated because this project is aimed to deliver a tool that supports the decision process. The methodology have to guide the process addressing implications and gain insight at which points in the manufacturing process producing end-products with AM is effective for them compared to traditional methods. At the highest detail level there are hundreds alternatives to consider. A tool should be developed that assists in the prioritization of those alternatives. Decision making tools assists the user in making full use of AM. Such a decision tool is unbiased and advises the best possible result without constraints in the generation of alternatives.

Ultimately, the goal is that Capgemini consultants with little AM knowledge together with clients are able to identifying appropriate opportunities to assess the impacts of using AM by asking relevant questions. Most of the time Capgemini is the first touch point for large organisations to come in contact with new technologies. The AIE can help these organisations to discover the relevance and impact of such technologies.

2. THEORETICAL FRAMEWORK FOR THE AM ASSESSMENT

2.1. Introduction

The literature review covers the elements necessary to develop an assessment methodology for AM assisted by decision support system. In order to answer the research questions, the literature review aims to clarify the statements made in the research questions. In this chapter the literature and context is reviewed from three perspectives:

- Additive manufacturing (AM),
- Analysis of existing assessment methodologies,
- Decision Support Systems (DSS).

Approaching this project from three directions results in a system which supports the decision making and evaluation of the possibilities that AM offers. Thorough understanding of all three concepts is necessary to develop a valuable assessment methodology. On the one hand the current situation of AM is reviewed to obtain a good understanding of the field. This information is required to develop an assessment methodology that can create a common understanding and is able to determine the impact on products. Comparing AM with other manufacturing methods is described to gain insight in the consideration factors to select an appropriate manufacturing technology. On the other hand an analysis of the current methodologies is described. It is defined to which extend current methods are able to identify appropriate business cases. Furthermore, shortcomings and disadvantages are investigated to provide sufficient basis for the development of methodology.

Finally, DSS's are assumed to be a good way to provide insight and understanding of the AM technology. The goal of this review is to structure the required information and identify how to and present the information and knowledge.

2.2. Position of Additive manufacturing in part production

This section presents the literature review with a general overview and is followed by discussing the current situation of AM, interesting gaps in literature, trends and challenges relevant for companies assessing the possibilities of AM. The additive manufacturing technology is continuously evolving and therefore it is important to keep up to date with limitations and new possibilities when investigating this technology.

2.2.1. Overview

AM is defined by the ASTM as the process of joining materials to make objects from digital 3D models, usually adding material layer-by-layer, as opposed to subtractive methods (ASTM International, 2012). Gibson, Rosen, & Stucker (2010) defined eight steps in the generic process of AM from Computer Aided Design (CAD) to production

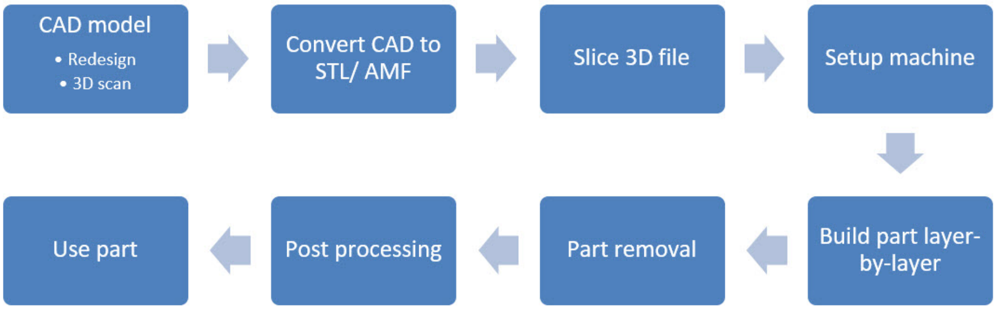


Figure 2.1. AM Process *Source: Gibson et al. (2010)*

1. **Conceptualization and CAD;** a CAD model is obtained by making a 3D scan, a product redesign or the 3D model is downloaded.
2. **Convert CAD file;** to file format suitable for AM software (i.e. AMF, STL etc.)
3. **Transfer and manipulate 3D model;** Slices the 3D model and generates support structures when needed,
4. **Machine setup;** pre-processing activities, prepare machine,
5. **Build step;** produces the part layer-by-layer,
6. **Part removal;** removes support structures and cleans up machine,
7. **Post-processing of part;** finishing the part for application, for example polishing, coating or in some cases performing chemical or thermal treatments,
8. **Application;** is the last step where the product is being used.

In the late 80's the first AM process started as a production method to make prototypes under the name rapid prototyping. Later the technology developed to rapid tooling, where it is used to produce tools (Gibson et al., 2010). Since then, technology emerged and now also final parts can be produced. While technology is already around for almost 40 years, according to Gartner (2015), improvements in AM technologies are heading towards an inflection point where parts can be produce for end-use purposes Figure 2.2 shows the Gartner hype cycle and shows that enterprise 3D printing has entered the slope of enlightenment (Gartner Inc., 2015).

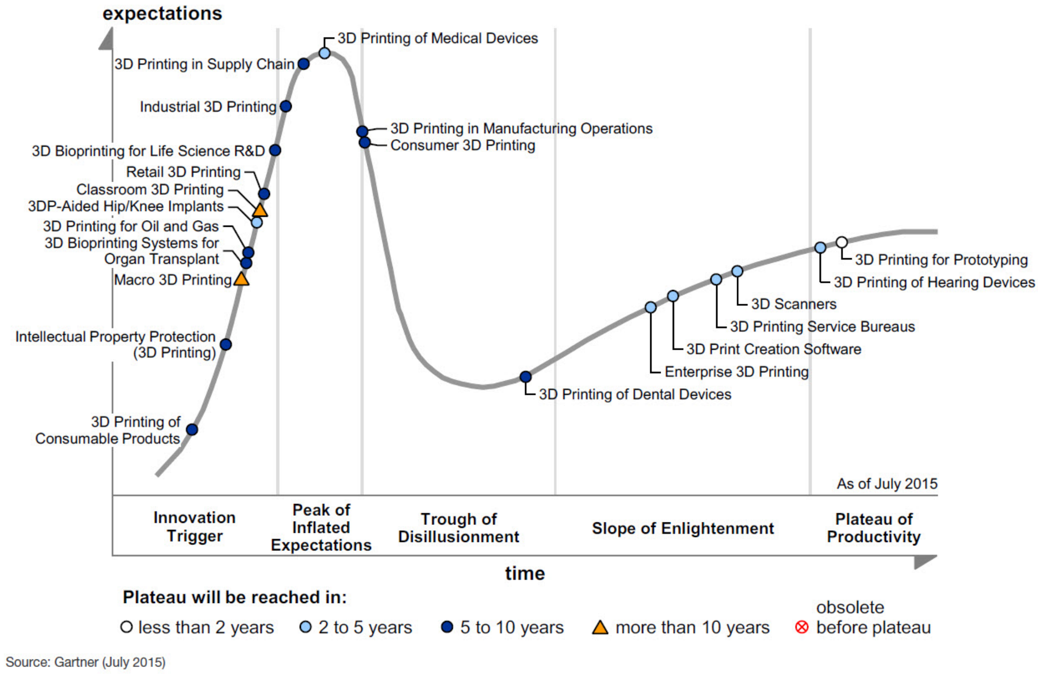


Figure 2.2. Gartner hype cycle 3D printing 2015 *Source: Gartner (2015)*

2.2.2. Current situation AM

According to Gartner (2015) this inflection point is caused by the improving technical capabilities and the increasing quality of AM machines while costs go down. These trends result in an increased use of AM in the production of final parts (Hague, Mansour, & Saleh, 2015). Using AM as a tool for producing end use parts is relatively new and there are some large scale applications in the aerospace, dental, medical, motor sports and jewellery industries (Wohlers, 2014). Mellor (2014) suggests that these developments will have an impact on companies, products and processes. Wise deployment of AM can result in new opportunities for products and businesses. Therefore, different technology orientated corporations are developing strategies for using AM as a technology to produce end parts in the near future (Wohlers, 2014).

In order to reach wide spread adoption of the technology the existing barriers such as size, speed and costs need to be solved to make the use of AM economically feasible. A lack of understanding of these barriers of AM leads to failure and unsuccessful commercialisation (Mellor, 2014). One of the main challenges is finding and translating the opportunities to real world applications and finding new ways to create value (Stratasys Direct, 2015). Using AM for final parts is new and it is one of the possibilities companies could use to increase value for their customers.

Leveraging the full potential of AM applications is possible when businesses make use of the special characteristics of AM. New design capabilities emerge when using the advantages of AM while finding solutions to handle existing challenges. Former design for manufacturing (DfM) constraints do not apply when using a layer-by-layer process. Compared to traditional manufacturing methods, AM has special characteristics that offer new possibilities especially in geometric complexity (Doubrovski et al., 2011).

2.2.3. Technologies

Additive manufacturing is an umbrella term for multiple types of technologies and processes. AM technologies are based on a layer-by-layer approach, but they vary in technologies used, materials and processes. In 2012 the ASTM defined seven categories of AM processes (ASTM International, 2012). Each category has differences in their capabilities affecting the usage in different applications or industries. The categories are shown in Table 2.1. For a detailed explanation of each technology see appendix 8.1.

Process name	Description
Sheet lamination	Sheets of materials are cut, stacked and bound together to form an object.
Binder jetting	A liquid bonding agent is selectively deposited to join powder material.
Material extrusion	Materials are heated and selectively dispensed through a nozzle.
Directed energy deposition	Focused thermal energy, such as a laser, is used to fuse materials by melting as the materials are being deposited to form an object.
Powder bed fusion	Thermal energy selectively fuses regions of a powder bed.
Material jetting	Materials, such as photopolymers or waxes, are selectively dispensed through a nozzle.
Vat photo polymerization	Certain types of light, such as ultraviolet light, to selectively solidify liquid photopolymers.

Table 2.1. AM technologies *Source: ASTM (2012)*

2.2.4. Opportunities and challenges

There are multiple opportunities identified as competitive advantages by an increasing number of companies (Cotteleer, 2014; Persons, 2015). Using flexible production methods like AM, small batch sizes become affordable because they are not affected by the economies of scale. The initial setup costs for AM are cheaper than for traditional manufacturing methods because expensive tooling like moulds and fixtures are not required (Berman, 2012). Furthermore, complexity of geometry can be increased while not affecting the production costs due to the lack of tooling, which results in more integrated functionality. In contrast, traditional manufacturing methods are in general cheaper for larger batch sizes because the costs per part can be spread over the total production volume. The effects of AM compared to traditional manufacturing are shown in Figure 2.3. The figure show the relation between the cost per part and the total number of parts produced. As can be seen the break-even point between injection moulding (IM) and different AM cost models varies between the model from Ruffo (break-even at 9000 parts) and Hopkinson and Dickens (break-even at 14000 parts). This show that the assumptions made in these calculations have to be considered carefully to prevent wrong expectations.

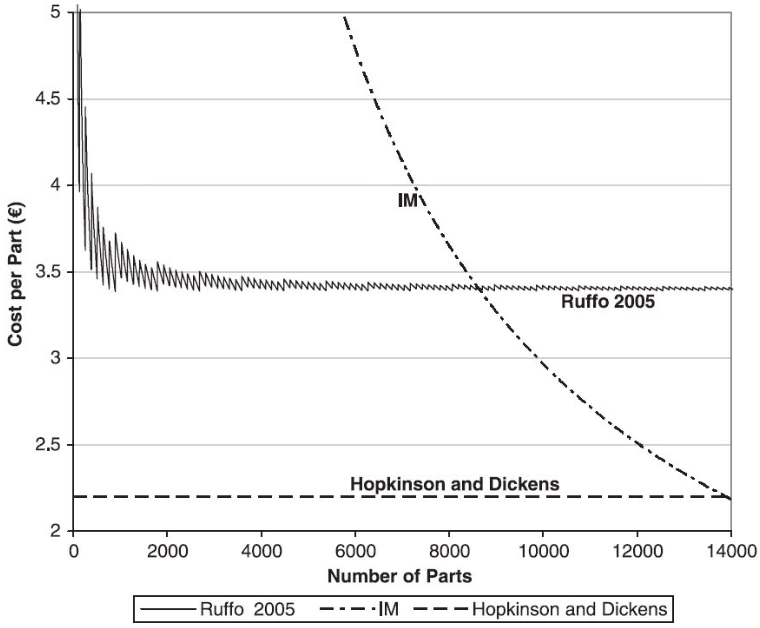


Figure 2.3. Break even analysis of AM costs comparted to IM Source: Ruffo (2006)

AM is applicable for small production series because of the low initial starting costs (Berman, 2012; Ruffo, Tuck, & Hague, 2006). Due to the elimination of tooling, lead times will be brought down and costs in the initial phases of the product development process are reduced (Hopkinson & Dickens, 2003).

Listing the benefits and limitations cannot clearly be defined in general, not all benefits apply to all situations. These limitations are a matter of perspective, in one case one should take the limitations into account and in other cases it is not relevant. However, AM offers businesses a number of unique benefits within a broad range of areas. Tuck et al. (2011) argues that the adoption of AM is also likely to enable new business models. These features the production of customised or high value products, diversified product portfolios, dematerialisation of supply chains, distributed manufacturing operations, more frequent product improvements and process innovations. The following list provides a good direction of the possible advantages and is a combination of multiple authors (Holmström, Partanen, Tuomi, & Walter, 2010; Negi, Dhiman, & Sharma, 2012; Petrovic et al., 2011; P. Reeves, 2008). Holmström et al. (2010) focuses on production benefits and Reeves (2008) focussed primarily on the supply chain benefits. The following list introduces some of the most common benefits of AM:

- **Best cost effective solution.** In some cases AM is the most cost-effective alternative compared to traditional methods for example due to the elimination of tooling (i.e. moulds) which required high upfront capital investment. The use of AM is cost-effective is for example when the production volumes are low, time-to-market is critical and product complexity is high,
- **Product customisation and personalisation.** Without the need for tooling, small production batches becomes economically feasible because of the increased flexibility in the design of the product which allows for product customisation and personalisation,
- **Reduction of time-to-market** due to the flexibility and speed of the process and the

independence on tooling, the lead times can be reduced. AM allows faster development cycles from the design to the manufacturing phase,

- **Increased flexibility** enables a possibility to quickly change design at lower costs. The technology is adaptable, very responsive which enables fast change over times. These characteristics are often required in agile and lean processes,
- **Risk reduction** Companies who want to test products quickly can launch products with low capital investment and thus far less risk. AM is in particular suitable for these fast tests, in combination with an AM service provider the capital risks are reduced to a minimum.
- **Distributed manufacturing.** Products can be produced at multiple locations closer to the consumer, this reduces the need for transportation and reduces the transportation costs. Also there is no need for a central inventory which has effect on the storage costs.
- **Supply chain simplification** Potential for simpler supply chains; shorter lead times, lower inventories,
- **Complexity could be increased** without cost penalty. Compared to traditional manufacturing methods, AM can manufacture parts almost free from geometric and manufacturing constraints. As a result companies can combine parts, reducing manufacturing and assembly costs. *Lightweight products;* Additionally, with topological optimisation the weight of products can be reduced, with this method complex structures are generated with an optimal strength to weight ratio and the amount of material can be reduced.
- **Function integration** allows products to be optimized for function. With the increased complexity of geometry, function integration becomes possible. Internal cooling channels are not constrained anymore by the manufacturing technology. Compared to injection moulding variable wall thickness and internal structures like honeycombs and lattice structures are possible.
- **Functionally graded materials.** With the layer-by-layer characteristic, extra functionality can be added to parts. For example porosity for medical implants can be integrated to promote cell growth and a material can have variable mechanical properties within a single part.
- **Efficient use of materials.** Material is added and not subtracted, in some examples in the metal sector they show a waste reduction up to 40% when using AM instead of conventional manufacturing.

However AM has still some challenges, of which some of them will be solved in the near future. Some issues restrict the use in certain application areas. Currently the major technical AM challenges are, build speed, accuracy, repeatability, surface finishing, post-processing methods, material and system costs (Thomas & Gilbert, 2014). But apart from these often more technical challenges, the lack of international product standards, process certifications, intellectual property and other legal issues can cause potential challenges to AM adoption, especially for the productions of end use commercial parts (Mellor, 2014). In the section below some AM specific issues are addressed obtained from multiple authors (Allison & Scudamore, 2014; Frazier, 2014; Mellor, 2014; Petrovic & Gonzalez, 2011; Piazza & Alexander, 2015; Phil Reeves & Mendis, 2015):

- **Standards and certification is lacking**. To ensure a good quality product industry standards are needed. Many industries have a need for certified products, this is one of the reason why organisations are reluctant to use AM,
- **Intellectual property considerations.** The only thing you need to reproduce a product is a 3D CAD file, these are easily sharable and could be send all over the world where

companies cannot track the spreading of the digital files,

- **Complex process control.** Parts that are produced at different machines at different locations require the process controls specific to the environmental conditions to guarantee the quality of the part,
- **Quality control** AM processes are not yet capable of reliably producing parts within the specification limits continuously which results in performing quality checks on every part separately;
- **Developing and characterizing new materials for AM.** The variety in metals are immature compared to traditional manufacturing methods. Many materials need more research before they can be used in AM processes;
- **Characterisation of mechanical and thermal properties.** AM parts behave in non-linear manner and the behaviour is not identical in all directions which causes a non-uniform material strength is in all directions. It depends on the layer build orientation, load applied along the build direction are stronger than other directions. Users of AM will fully trust the technology when a part can be characterized properly;
- **High AM system and material costs.** Currently AM systems and materials for industrial uses are very expensive due to the high manufacturing costs. These costs are inherent at the introduction of new technologies. When the amount of users are increases, system and material costs can be reduced. However, there are some low cost alternatives available aiming at the entry level users primarily for personal use. Because the unfamiliarity with a new technology organisations have difficulties with the economic considerations and cost justification of using AM.
- **Software capabilities,** almost all CAD modelling programs are designed for traditional manufacturing methods. Making organic shapes is hard and often not good supported. Topology optimisation methods are not integrated in the most common CAD software packages. Rhinoceros is one of the few CAD modelling software packages which is able to build generative designs. Furthermore, the STL file format is the industry standard but it has some limitations, it is large and the geometry is reduced and cannot support multi material products.
- **Education of designers and engineers.** AM enables the use of complex shapes which are less constrained by the manufacturing technology. Creating a new AM mindset is required to make full use of the process capabilities. Education is still focused on conventional manufacturing
- **Improving the surface quality and surface roughness.** The layer-by-layer production causes a stair stepping effect depending on the direction of the build direction.
- **Low accuracy in the z-direction is the result of the layer thickness.** The smaller the layer thickness the higher the resolution of the part/ in contrast the smaller the layer thickness the longer the build time.
- **The use of support structures.** The support structures sometimes affect the part quality. Optimizing the build direction should minimize the amount of support structures.

According to Allison & Scudamore (2014) there are certain expectations that needs to be managed before applying or evaluating AM. Understanding of the AM capabilities; design, material, costs and properties can be obtained with a central database that contains knowledge to identify the best application match (Kerwien et al., 2013). Such a knowledge base with AM knowledge could improve the effectiveness of production and support the identification of opportunities. The benefits and challenges described above are captured in a variety of applications in a diverse range of industries and different stages of the product development life cycle. These challenges affect product portfolios and business processes.

Many executives, managers, and financial professionals find themselves trying to understand the AM business case specific to their organisation (Cotteleer, 2014).

2.2.5. AM applications

AM can be used in different stages of the product life cycle and has various applications in different industries. Applications can be categorised into three types of use cases, rapid prototyping, rapid tooling and rapid manufacturing (or direct manufacturing).

- **Rapid prototyping** was one of the first usages of AM. Originally it was designed to improve the prototyping process because manufacturers find prototyping a complex and expensive process (Gibson et al., 2010). Still, a large percentage of the uses for AM are making prototype verifications and performing fit and function testing (Hague, Campbell, & Dickens, 2003)
- **Rapid tooling** refers to the use of AM to create production tools to support traditional manufacturing processes and can be considered as a sub category of rapid manufacturing (Achillas, Aidonis, Iakovou, Thymianidis, & Tzetzis, 2014). For short run production series making moulds and fixtures with this type has to be considered. The objective is to obtain a tool quickly and at low costs. Another application is the production of casting patterns, due to the capabilities of AM to produce complex parts, moulds can be made as a secondary process. Investment casting (also called lost wax method) is one of these processes that is an indirect application of AM.
- **Rapid manufacturing** (Direct manufacturing) is the use of AM technology for end-use purposes. In recent years this has been subject of many studies.

All applications are important but the greatest value for AM lies in the production of end use parts that benefit from the capabilities (Gausemeier, Wall, & Peter, 2013). Figure 2.4 shows the usage of AM parts. Since a couple of years the use of AM is moving towards end use production. Where in 1999 only 16% of the parts were functional models, in 2014 29% of applications are produced for end-use (Wohlers, 2014).

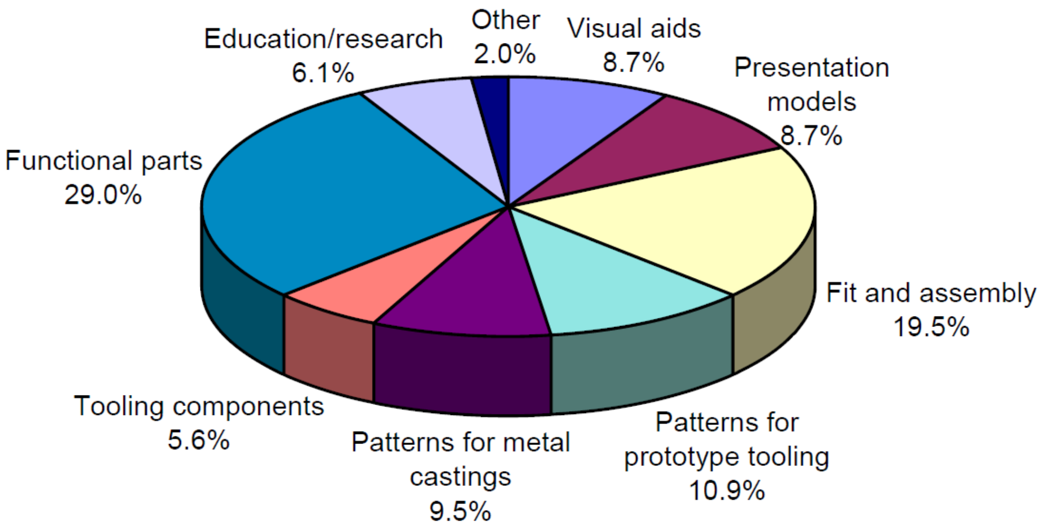


Figure 2.4. Overview of the application types in the AM industry *Source: Wohlers (2014)*

Application in industries

AM can be used in different industries for a variety of applications. Each industry has its own characteristic and uses AM to improve the efficiency of the process or enhance the performance of the products. Wohlers conducted a survey in which AM companies were asked to indicate what percentage of revenue came from which industry (Wohlers, 2014). As can be seen in Figure 2.5 the industrial/business machines is the largest industry for AM, closely followed by the consumer products and electronics industries. The consumer products include many types of products from toys to kitchen tools. These products can be characterised as mass produced goods with short product life cycles. AM is often used for prototyping to increase the speed of the product development in industries with these characteristics. Two other industries where AM can be used worth mentioning are the motor vehicles and the medical/ dental industry. The motor vehicles includes automotive, Formula 1 and motorized sports, the focus for end-use products is often on reducing weight with the use of topological optimisation. The medical industry is using AM for making models, prosthetics and orthopaedic implants for example hip and knee implants. The dental industry have difficulties with long lead times and the labour intensiveness of making orthodontic aligners, crowns and bridges. With AM this process can be made more efficient, with advanced 3D scanning tools these products can be produced faster.
In the aerospace industry the use of AM is interesting because the weight of parts can be reduced and complex assemblies can be consolidated in simple parts. At this moment AM is only used in parts that are not mission critical because the parts cannot be fully certified.

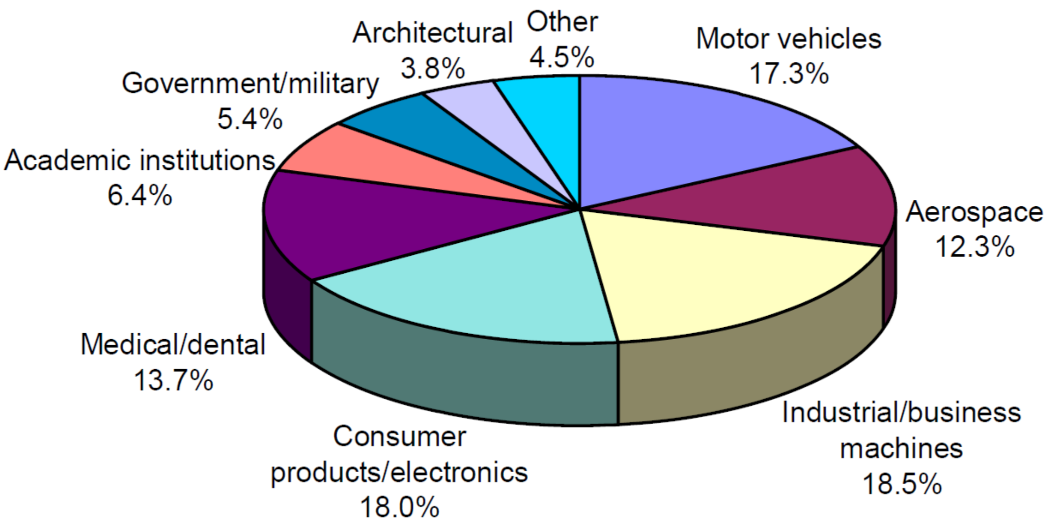


Figure 2.5. Overview of the AM revenue per industry sector *Source: Wohlers (2014)*

2.2.6. Traditional manufacturing

Understanding business cases and finding applications for AM, require consideration of manufacturing alternatives that might be better suited or more cost effective. Current manufacturing technologies can be characterized as additive, subtractive (i.e. CNC milling and cutting) and formative technologies (i.e. injection moulding) of which the latter two are defined as the traditional methods.

Subtractive manufacturing removes material from a block to form the final product geometry. Subtractive manufacturing is defined through milling, turning, boring, or cutting processes most of the time digitally controlled through CNC. Some advantages of subtractive manufacturing are parts produced in this manner can be certified easily. The most important disadvantage are the constraints in the complexity of the geometries produced due to the limitations caused by tooling. The design goals of subtractive manufacturing is to make components simple to keep costs low and feasible.

Formative manufacturing uses moulds with a negative shape to create the positive shape. The mould is usually made from metal but depending on the application this could also be made from plastics or sand as used in metal casting. Designing and making moulds requires thorough knowledge of the process and it is resource intensive. End products from for example injection moulding have a high surface quality that can be mass manufactured which is an important factor in the manufacturing industry.

Identifying when to use traditional manufacturing over AM requires consideration of three highly connected factors; the design, the material and the process (Shercliff & Lovatt, 2001). The design (technical requirements) define the scope of the process selection whether the attributes of a manufacturing method are able to meet the most important requirements. Materials can be described in a set of properties which also can give direction to the process selection. Process factors are constrained by the capabilities of the available machines, for example the materials, accuracy and part size.

Product designers and engineers are familiar with conventional production techniques and are naturally biased towards them. Some researchers argue that there is a so called 'psychological inertia', which means that designers are used to design for traditional production processes and fail to identify and exploit the capabilities AM offers. This way of thinking is embedded in a company's culture and is the most difficult thing to change (Wohlers, 2014). The need to develop solutions that aid designers and engineers in achieving an optimal design for AM is widely recognized within literature (Allison & Scudamore, 2014). Because of the bias towards traditional manufacturing companies are not able to discover economic benefits, due to their conventional ways of determining appropriateness.

Besides the technical considerations of AM there are non-technical challenges that need to be solved to stimulate adoption of AM for end-use parts. Piazza & Alexander (2015) have identified three factors that cause a bias towards conventional manufacturing.

1. Designers, engineers and business people are used to Design for manufacturing (DfM) considerations and think often in economies of scale;
2. Most manufactures see AM as a tool for prototyping but not for real productions runs. (McCutcheon, Pethikc, Bono, & Thut, 2014)
3. Applications for AM are unknown, have an unclear benefit and no awareness cause a bias toward the tradition manufacturing methods.

Allison & Scudamore (2014) mentions a lack of education of AM practitioners in the AM capabilities. For businesses it is still unknown how to make use of AM technology. In order to overcome these barriers they recommend raising awareness of AM technology through knowledge transfer and educating the general public to enhance interest in AM applications. Furthermore, Geraedts & Doubrovski (2012) mention that education is still focused on classic design methodologies like Design for Manufacturing (DfM). Despite a growing body of knowledge concerning technical challenges, there is a lack of methods that allow designers to effectively deal with the new possibilities. Doubrovski et al. (2011) discusses the question, how designers should change their way of working and how to allow designers to deal with this new technology.

Design for manufacturing

Design for manufacturing (DfM) is a mindset in which manufacturing input is used at the earliest stages of design, used to produce products easily and economically. DfM is an aspect of the design process in which manufacturing considerations are explicitly used to influence the design. The most important principle is to design for ease of manufacturing, which is different for each manufacturing method. Designers and engineers have been educated to develop designs which are restricted by manufacturing considerations to produce products easily (Hague et al., 2003).
One of the most restricting factors in product development is the need for tooling in conventional manufacturing. With AM there is no dependence on tooling which means that traditional restrictions for design for manufacturing are no longer valid (Hague et al., 2015). The ability to produce complex geometries means that we need a new dimension of 'manufacture for design' rather than the more conventional DfM philosophy (Campbell, Hague, Sener, & Wormald, 2003). In addition there is no longer a need to produce parts in large batch sizes in order to amortize the cost of the tooling.

Design for additive manufacturing

Designing for AM requires different approaches to the design process. By using AM, geometric complexity is no longer a limiting factor. This will have a considerable impact on design and the working methods of designers. An important aspect of AM is the freedom in design. Developing and producing complex geometry without the need for tooling could significantly reduce the lead times and possibly reduce the overall manufacturing costs. The tool-less approach of AM has profound implications on the way designers are used to do their work and this eliminates most DfM considerations (Hague et al., 2015). Without the need for tooling many of the current restrictions of design for manufacturing are no longer valid (Pessard, Mognol, Hascoët, & Gerometta, 2008). Some researchers deny that AM technologies have any manufacturing constraints (Gibson et al., 2010; Hague et al., 2003). This statement is often repeated in mainstream media (Conner et al., 2014). As with all manufacturing processes, AM has specific characteristics and constrains that have an impact on the manufactured parts (Wohlers, 2014). These design constraints are generally captured in design rules and guidelines. Design guidelines require extensive knowledge of the manufacturing process and material behaviour. For example when developing a part with a small hole diameter in a thick plate, due to the roughness of the SLS process the hole will be completely closed (Govett et al., 2012).
Figure 2.6 shows a test setup with results for finding the minimum hole diameter with various depths and the distance between themselves. The results indicate that holes which

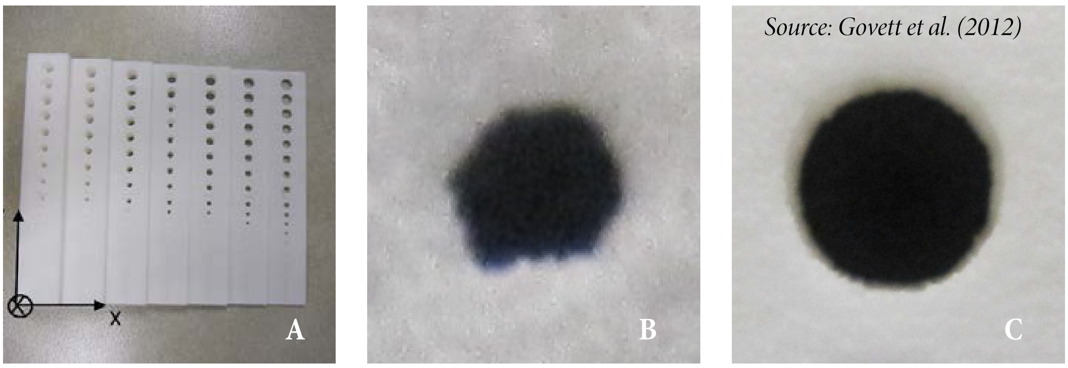


Figure 2.6. Test setup(A) with results (B and C) of minimum hole diameters for SLS.

are deeper should have a greater diameter to prevent irregular shaped circles (see fig 2.6 B). In table 2.2 the differences between DfM and DfAM are shown. Limitations and key principles of the traditional methods are compared to the advantages and capabilities of AM.

	Design for manufacturing (DFM)	Design for AM (DfAM)
Constraints	Understanding of the manufacturing constraints at an early stage is important to design products to minimize constraint violation. (Gibson et al., 2010, p. 402)	The challenge in AM are not the manufacturing constraints of AM but designers should rather consider the opportunities and functionalities. (Gibson et al., 2010, p. 413)
Complexity and geometrical freedom	A key limiting factor for the complexity is the ability of tools to reach and fabricate specific features of the part. (Gibson et al., 2010, p. 405)	Due to the layer-by-layer principle the process can reach and build up material at any point. Geometric complexity is virtually unlimited (Gibson et al., 2010, p. 405).
Costs	The costs in traditional manufacturing are directly linked to the complexity because they require more effort. (Hopkinson & Dickens, 2006, p. 5)	The complexity of a product does not directly influence the costs. Major cost drivers for AM are material and machine costs (Thomas et al., 2014, p. 16)
Material	Parts are formed in moulds are generally in one homogeneous material, even with an over moulded component there is a clear boundary. (Hopkinson & Dickens, 2006, p. 16)	With DfAM a part can have a functionally graded material of which material properties can differ in the same part (Hopkinson & Dickens, 2006, p. 16).
Late Design changes	Late design changes are costly	Design changes can be made easily due to the responsiveness character of AM (Royal Academy of Engineering, 2013).
Production volume and variety	Mostly, designs are uniform and generic to keep it cost-effective. The tooling of the parts have to be amortised over many components. (Hague et al., 2003, p. 29)	AM enables production of customized and personalised shapes more cost-effectively (Hague et al., 2003)
Assembly	In an optimal situation the manufacturing difficulties are reduced compared to the extra assembly effort of multiple parts. (Gibson et al., 2010, p. 403)	Reduced part count and integrated assembly is possible. However there remains a clear need for design for assembly for components like circuit boards and batteries. (Hague et al., 2003, p. 29)
Standards and certification	Clear standards and predictive models exists for traditional manufacturing methods this makes parts produced with traditional methods often more easily certifiable (Kerwien et al., 2013)	Standards and certifications are not yet fully adapted for AM. More effort should be put into the certification of AM produced parts (Bauer, Systems, & Malone, 2015, p. 5).
Design software	CAD design systems are designed for models relative simple geometries which consists of basic geometric features (Royal Academy of Engineering, 2013, p. 15).	New CAD systems with advanced modelling capabilities are needed to design complex generative designs (Gibson et al., 2010, p. 416).

Table 2.2. Comparison of DfM to DfAM

AM mindset

Comparing AM to traditional manufacturing methods is relevant in situations where the characteristic of AM might be advantageous. Determining when AM is applicable depends on context and the product specifications. Taking into consideration the capabilities (and constraints) of AM requires a deep understanding of AM processes and of their design implications.

High level functional requirements have to be clear when considering alternative manufacturing technologies. In case of redesign, these requirements are often well known, when developing a new product these requirements are unknown and assumptions have to be made.

Tuck, Hague, Ruffo, Ransley, & Adams (2011) identified two main advantages of AM compared to traditional manufacturing. Firstly, AM may enable production without many of the constraints on part geometry that do apply to other techniques which lead to products featuring a complex geometry and integrated functionalities. Secondly, AM allows to manufacture highly customised products in small quantities at a relatively low cost. For each situation a trade-off should be made where AM has an advantage over the traditional manufacturing capabilities in relation to the product requirements. AM requires consideration of the part complexity, material, part quantity, part size, overall quality, production costs and the lead-time when comparing to traditional manufacturing methods (Conner et al., 2014; Sculpteo, 2014). In the following list each characteristic will be described and provides insight in the differences of the manufacturing methods.

- **Quantity** is defined by the size of the production run. Traditional manufacturing are more suitable for large scale manufacturing where AM is better suited for producing low volumes economically.
- **Lead time** differs a between both methods. With traditional manufacturing often tooling is needed which requires a significant amount of time before the production can be started. In contrast, AM can produce products directly on demand and is not reliant on tooling.
- **Complexity** differentiates AM from traditional manufacturing. Where the complexity of a part has a lot of influence on the costs with traditional manufacturing, there is not a clear relation between costs and complexity with AM. Complexity can be defined on the basis of the following list (Atzeni & Salmi, 2012).
    - *Features:* thin and variable wall thickness, undercuts, deep channels, internal channels.
    - *Geometries* with twisted and contorted shapes, hollow spaces, lattices, topologically optimized organic shapes and fine detail parts,
    - *Parts consolidation*: integrated parts that would otherwise be welded or joined together into a single printed part
    - *Fabrication step consolidation*: nesting parts that would be assembled in multiple steps if fabricated conventionally can be printed simultaneously.
- **Material selection** for AM is much more limited compared to traditional methods.
- **Part size** is currently a limiting factor for AM for most techniques. Where traditional methods have comparatively more differentiated machines, the build envelope for AM is small. The smaller the part, the more can be printed in one build, this increases the production and cost efficiency.
- **Production costs** are for AM is currently higher than traditional manufacturing. In most cases, when the capabilities of AM add value the production costs can be justified

more easily,

- **Overall quality** can be defined as accuracy, tolerances and surface finish and the importance is defined by the intended use of the product. Quality in manufacturing is defined in this thesis through the constant accuracy on surface and features of produced products.
    - *Accuracy and tolerances* for AM depend of the manufacturing method chosen. An important factor is the thickness of a layer which defines the overall accuracy of AM.
    - *Surface finish* is in some applications of high importance. Some AM technologies are able to produce a smooth surface finish but these do not have the right material properties for an end use product.

Identifying the situations where the use of AM benefits from its capabilities is the main challenge. The advantages of AM have to be in close consideration with the limitations of the technology. In some cases the limitations are more important than the advantages when considering as a direct replacement.

Economic considerations

After technical considering whether it is possible to produce a part, often multiple alternatives remain. To make a selection of those alternatives, costs are often the decisive factor in the choice for a production method (Christian Lindemann & Jahnke, 2012). Generally AM is suited for the production of small and complex parts in low volumes (Wohlers, 2014). When comparing AM on the basis of costs the range of suited products is small. For example using AM for producing the identical parts in large volumes are rarely less expensive than conventional technologies. Determining the cost-effectiveness of parts require analysis of all lifecycle and supply chain costs. These in-depth analysis are out of scope in this research. Table 2.3 shows an overview of the characteristics in relation to different manufacturing technologies types. This table shows the process capabilities for each individual method without the use of post processing steps. For simplification purposes, the subtractive methods will only consider CNC machining and the formative methods injection moulding and sand casting. The capabilities of AM are split in the seven main AM categories. However, AM can also be chosen as a hybrid manufacturing method. Combing the capabilities of different manufacturing technologies might become feasible but these combinations are not visible in this table. technologies might become feasible but these combinations are not visible in this table.

Characteristic	Traditional manufacturing			Additive manufacturing						
	Subtractive	Formative		ME	BJ	DE	PB	MJ	VP	SL
	CNC	IM	Sand casting							
Costs (low volume)	–	✗	–	✓	✓	✓	✓	✓	✓	✓
Costs (high volume)	✗	✓	✓	✗	✗	✗	✗	✗	–	✗
Lead-time	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓
Geometric complexity	–	–	–	✓	✓	✓	✓	✓	✓	✓
Amount of available material	✓	✓	–	✗	✗	✗	–	✗	✗	✗
Maximum part size	✓	✓	✓	✗	✗	✓	–	✗	✗	✓
Overall accuracy	✓	✓	✓	✗	✗	✗	–	✓	✓	✗
Surface finish	✓	✓	✓	✗	✗	✗	–	–	–	✗

✓ is good, – is fair, ✗ is poor

IM= Injection moulding, ME= Material extrusion, BJ= Binder jetting, DE= Directed energy deposition, PB= Powder bed fusion, MJ= Material jetting, VP= Vat photo polymerization and SL= Sheet lamination

adapted from Sculpteo (2014)

Table 2.3. Differences between manufacturing technologies

2.2.7. Life cycle costing for AM

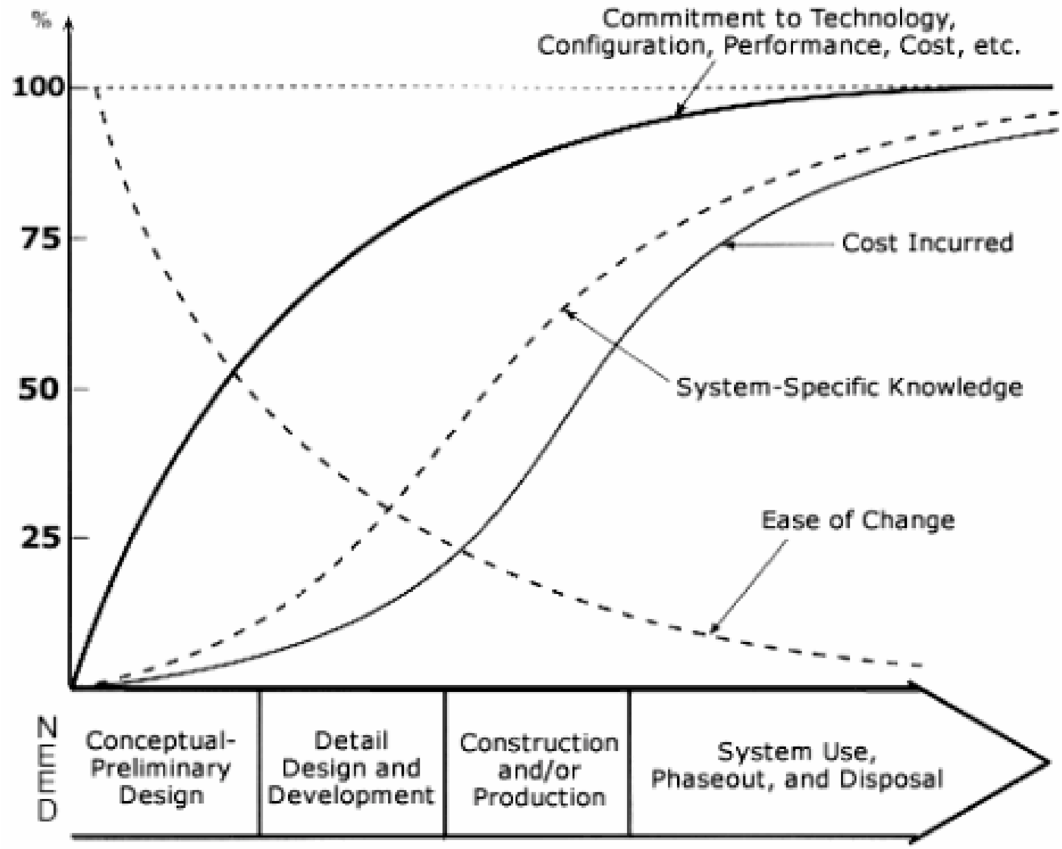


Figure 2.7. Costs of a system throughout the product lifecycle.
Source: (Blanchard & Fabrycky, 2008, p. 63)

Figure 2.7 shows that the most costs are defined in the early stages of the development of a product. Insight in the cost, at an early stage, is important to influence the decision making process. Therefore determining the cost effectiveness of AM has to be discussed. One of the reasons to adopt AM is when the costs of traditional methods exceed the costs of AM during the product life cycle. Gaining insights in the lifecycle costs of a certain products will help to identify appropriate applications.

Comparing AM to traditional manufacturing methods in terms of costs is possible when also attention is paid to the additional costs beside the production costs. Life cycle costs are depend on the type and the context of the product. In some cases it is important to investigate the costs besides the production. Costs occurred during the use and maintenance phase can help to determine the suitability of a specific alternative. For products with high service, usage and maintenance costs it can help to assess the lifecycle costs before decisions are made.

Calculating the costs for additive manufacturing is a complex endeavour. There are many variables that can be used in the calculation, in literature many authors only discuss the production costs (Hopkinson & Dickens, 2003; Ruffo et al., 2006). They do not incorporate the factors related to the supply chain and the rest of the lifecycle. Moreover, these authors investigate each production method individually, where in some cases benefit can be obtained when production methods are combined to make use of the capabilities of both technologies.

The costs structures for AM can be defined in two ways, well-structured costs and ill-structured costs. Most of the literature about AM costs uses well-structured costs however, some significant cost savings for AM can be obtained when ill-structured costs are used. This type of costs can be associated with build failure, machine setup, inventory and transportation. Furthermore the supply chain may also be influenced by AM. With the use of AM the supply chain is simplified because the technology has the possibility to manufacturer products closer to the consumers. In contrast, well-structured costs are related to labour, material, build time, energy and machine costs. Thomas & Gilbert (2014) found out two important cost drivers that define the costs for AM. First costs are related with the machine costs and second the material costs used by the AM machines.

Material costs for AM are currently higher than that of traditional materials. Machine costs are one of the highest costs in additive manufacturing and the difference between polymer- or metal-based systems are significant. Another factors that has impact on the costs for AM is firstly the build envelope, which constraints the outer dimensions of the parts and secondly effectiveness of utilisation this build space. The build time costs are related to the dimensions of the model, material and manufacturing system. Energy costs are important factors to consider when comparing AM to other methods particular in life cycle cost calculations. The energy used differs per manufacturing system and the utilisation of the build space. The labour costs are only a small part of the total AM costs. Labour costs include the time spend by an operator to remove finished product from the machine or prepare the machine. According to Hopkinson & Dickens (2003) and Ruffo et al (2006) the costs for labour are estimated at 2% of the total costs. A comparison of both cost models can be found in appendix 8.2.

Important to note is that some advantages of AM cannot be translated into costs directly. Furthermore in the future the costs of the materials and the system will likely to decrease due to the increased adoption of AM.

2.3. Benchmarking existing AM assessment methodologies

Currently, organisations are assessing the suitability and feasibility of using AM in their processes. This section analyses different AM assessment methodologies and tools and compares their capabilities. Available methodologies will be analysed that can help companies in assessing the value of AM.

Based on their goals with the methodology three types are identified. The first group aims to sell their expertise and knowledge by offering specialized services. These organisations, mostly consulting companies, can help to obtain insight in business opportunities. The main goal of the second group is to sell resources (i.e. physical 3D prints or information). Mostly these methodologies are web-based and are used for marketing purposes for example offer a stripped down version of insight in the benefit that can be obtained. Lastly, there are assessment methodologies developed by scientific organisation with the purpose of developing information. This review gives insight in the differences in characteristics like lead time, ease of use, scope and required amount of knowledge to determine which capabilities are relevant for Capgemini.

2.3.1. Selling knowledge and expertise

There are several companies offering consulting services that identify the applicability of AM. Consultants assist clients in the definition of strategies, offer specialized skills or have a different mindset to identify the potential of AM. Organisations often use these services to get another perspective on their business decisions and show them new ideas that clients would not have seen on their own. Consultants provide organisations with knowledge about technology to make reasoned decisions whether AM is a suitable production technology. These services often help to identify suitable business cases and introduce an AM strategy to make full use of a new manufacturing technology. Remarkably is that most AM machine manufacturers also provide consulting services to their customers to exploit the full potential of their AM machine.

Stratasys consulting

Stratasys sells AM systems and materials and recently they started to provide consulting services. Started in 2003 as Econolyst Ltd. is since the beginning of 2015 part of the Stratasys group as the consulting department. Clients who uses the services from Stratasys Consulting are supported in the development and implementation of AM throughout the lifecycle. According to Stratasys (2016) there is no one size fits all approach, but in broad terms it identifies short term and long term opportunities of AM for use in the business and supply chain. The target group is different for each project, but mainly Stratasys aims to sell machines and thus focusses on engineers, directors and other managing people. No technological knowledge is required, this expertise is availible at the consultants. The process (shown in Figure 2.8) consists of several steps and starts with explaining the capabilities and limitations of AM. In this first step the differences with traditional manufacturing are explained and possible business drivers or barriers are identified. This provides sufficient knowledge for the second step to ideate about products and services. Resulting ideas are then evaluated for economic and technical feasibility. Stratasys consulting (2016) uses different tools like, lifecycle modelling, LCA analysis, economic part modelling, part quality modelling, supply chain analysis and road mapping to build feasible business cases. In these analyses important considerations like costs, time, quality and process selection are evaluated. The last step is to ensure a sustainable end result, an AM strategy is developed that captures business wide implications (Stratasys Strategic Consulting, 2016).

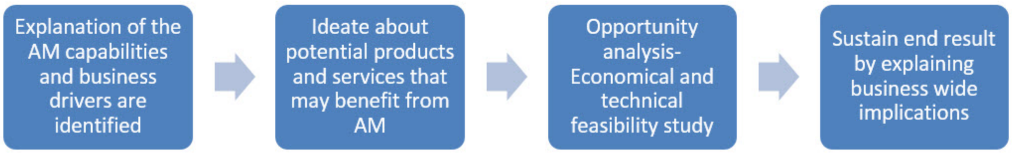


Figure 2.8. Stratasys Consulting process

EOS consulting

EOS manufactures and sells AM systems and materials, offers software solutions, provides support and consultancy services. The process is designed as a three day workshop and aims at companies who want to redesign products for the AM technology but are not able to find the right application with which to start. The assessment methodology of EOS Consulting is primarily focussed on part selection. The target group are employees in technical and commercial departments who wish to select specific components within their company and assess their economic and technical feasibility. Some technical knowledge is required to follow the methodology easily. In the EOS workshops the participants will learn the DfAM approach to identify the applications for AM. Obtaining the right mindset is done by providing the evaluators a profound understanding of the technical and economic feasibility. The technical knowledge is then used to identify appropriate parts suitable for AM. After the workshop the employees will have the knowledge to repeat the methodology to identify other parts that might be suitable for AM. The list below outlines the structure of the three day workshop (EOS Consulting, 2015).

1. Introduction to AM
2. Methodology of part assessment
3. Analysis of value chain
4. Evaluating selected parts
5. Principles of DfAM

Berenschot Consulting

Berenschot is an independent consultancy company and is also active in the AM field (Berenschot, 2012). They focus on process integration and identifies whether AM offers opportunities for new business development. The goal of the assessment is to construct a business case where the benefits of AM are applied. Berenschot provides a business perspective on the identification of opportunities and aims at technical department managers and business professionals.

During the project the organisation is interviewed and relevant information is obtained. Most of the work will be done by consultants and a report with action plan is handed over at the end of the project. The assessment process of Berenschot Consulting is shown in Figure 2.9 and consists of 5 steps and takes up to 16 weeks. The goal of the process is to identify a feasible AM business opportunities, ranging from products to new business models. The methodology starts with 1) analysing the market and potential customers, 2) translation of customer and market needs into possible AM solutions, 3) possible solutions are analysed for their technical feasibility, followed by 4) an analysis of the commercial feasibility where the business case is defined and a supply chain sketch is made. In the last step all analysis steps are put into an action plan (Ponfoort et al., 2012).

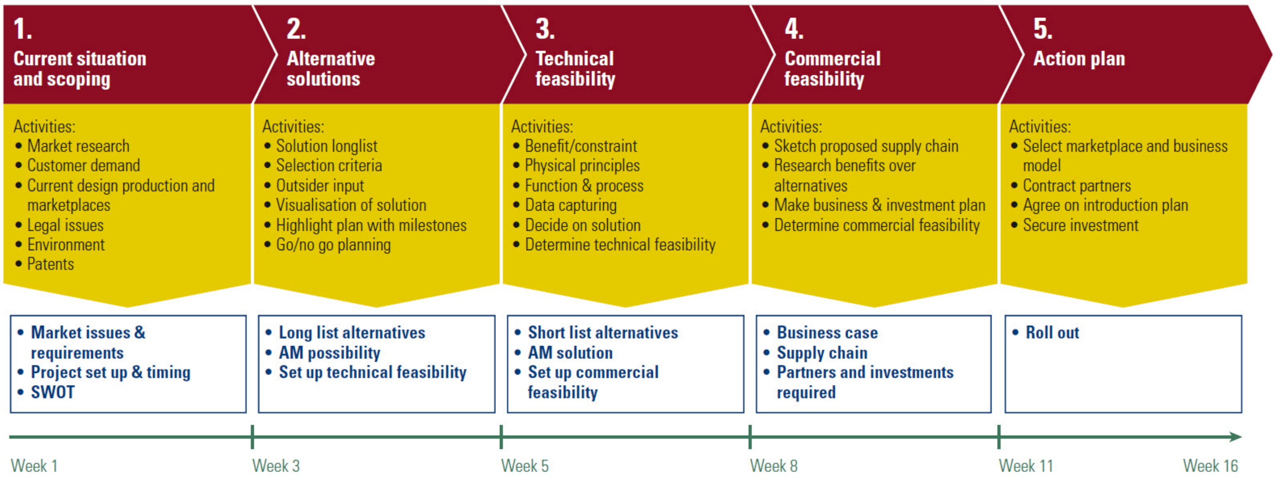


Figure 2.9. Berenschot consulting assessment process scheme *Source: Berenschot (2012)*

2.3.2. Selling resources

The methodologies described in this category often encourages to use their services. Often, the methodologies are web based tools that provide a new perspective on finding suitable AM opportunities. These tools are interactive and provide fast insight in the capabilities of AM but often lack in-depth analysis capabilities.
Web based tools provide a whole different perspective on finding suitable AM opportunities. These tools are interactive and provide fast insight in the capabilities of AM.

3D Print Barometer by Materialise
Materialise is a service provider of AM software and manufacturing services. The 3D print barometer is developed by Materialise and aims to give fast insight in the suitability of parts for AM. The tool, shown in Figure 2.10, helps engineers and designers in manufacturing companies discover parts that can benefit from AM. By specifying five product or project characteristics the suitability can be determined quickly. The five characteristics are, part size, part complexity, project value, batch size and the purpose. All these aspects have impact on the AM suitability (Materialise, 2016). Based on an internal algorithm calculating the matching percentage, the tool determines whether the project can benefit from AM. When there is a positive result (above 70%), chances are high that the product can benefit from AM and the user can contact Materialise for further development. Either way organisations are stimulated to contact Materialise to discuss the opportunities and capabilities which are not covered by this tool.

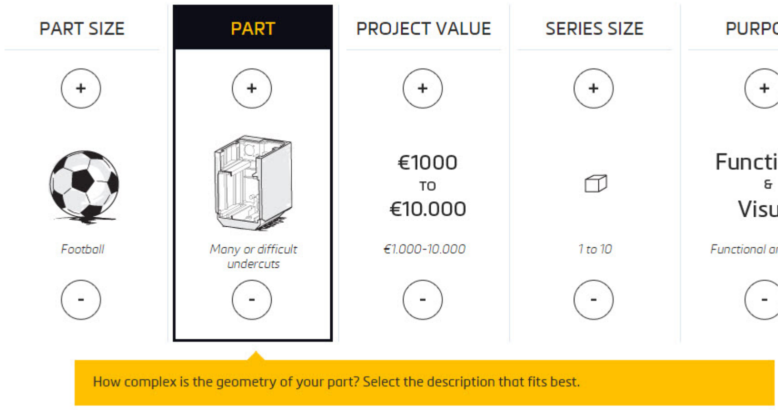


Figure 2.10. 3D Print Barometer *Source: Materialise (2016)*

Rapid prototyping navigator

The Rapid prototyping navigator is developed by Rapidprototyping.nl which is an independent branch of JB Ventures BV (JB Ventures, 2016). The tool, shown in Figure 2.11, aims at technical users who want production advice to produce prototypes. Compared to the 3D print barometer, this tool uses different characteristics with more specific quantification of requirements to define the suitability of AM. Based on a database with process capabilities of the available technologies a filtering is made. In the basis, the tool aims to identify a suitable AM technology but when the input values exceed the capabilities of AM, a traditional method is proposed. Characteristic used in this 'navigator' are the main dimensions, typical wall thickness, batch size, functionalities and time to delivery. The typical wall thickness is a determining factor because they say it determines the stability of the product during the production process. Another interesting factor is the functionality, this defines the goal or the environment of use for the part. Some AM processes are better suited to fulfil specific functionalities. The last defining factor is the selection for AM is the delivery time, when the product is needed quickly AM becomes faster a more suitable solution (Rapidprototyping.nl, 2016).

Another part of the tool is a prototyping calculator this requires more knowledge and can be applied further in the development process. Users can upload their STL files and select the amount, material, AM technology and a finish. The STL file contains the outer dimensions and the volume of the part. Based on these specifications costs are calculated (Rapidprototyping.nl, 2016).

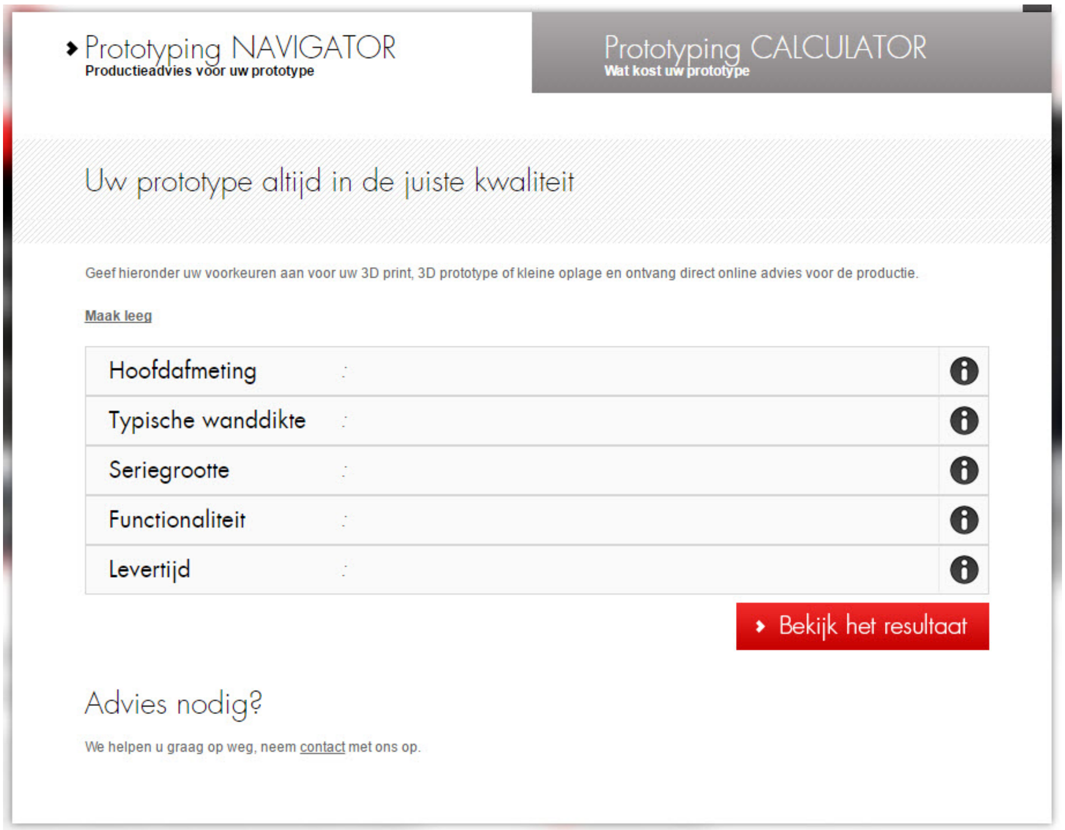
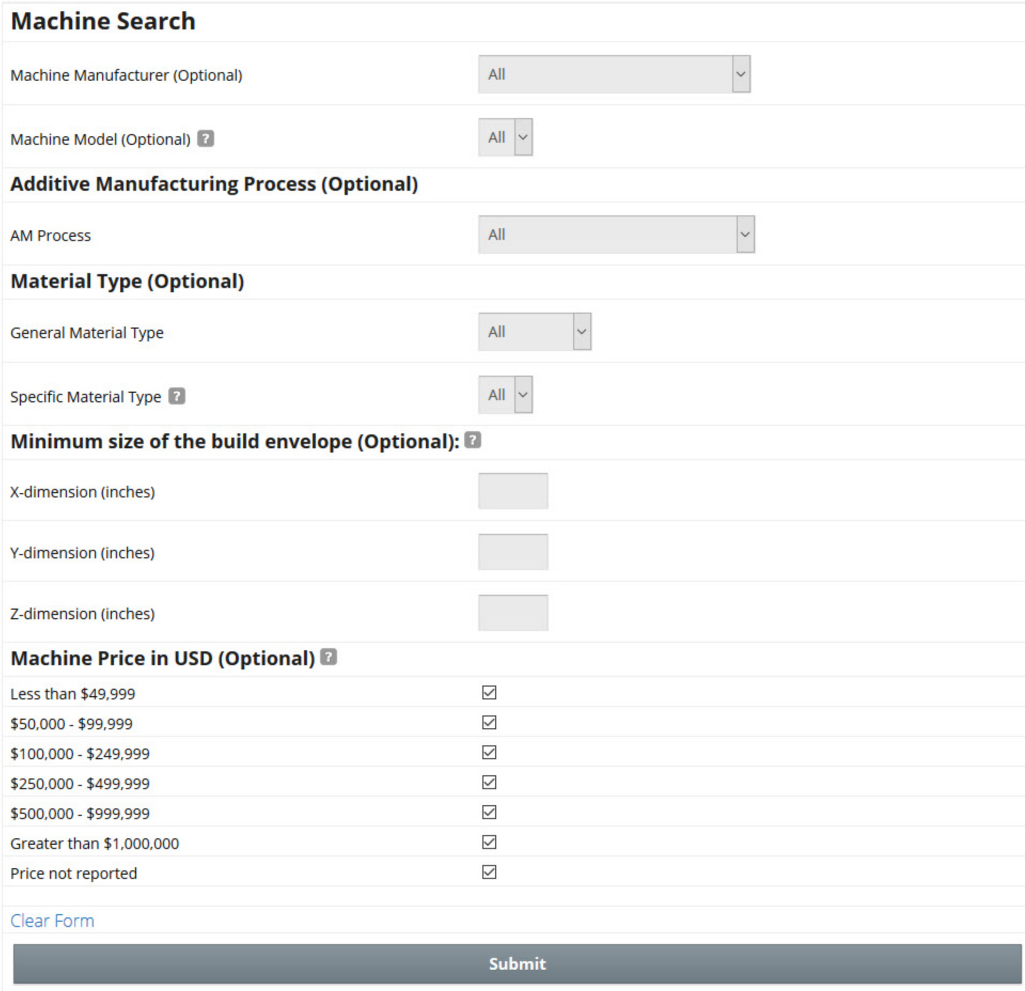


Figure 2.11. Rapid prototyping navigator *Source: Rapidprototyping.nl (2016)*

Senvol database

Senvol provides data to help companies implement AM in their organisation. Their products and services range from different databases to indexes with data of materials, machines and process parameters. These databases require technical knowledge and can be used by technical users from the concept definition stages in the product development. The Senvol database is divided in two parts, a machine seach (shown in Figure 2.12) and materials search functionality. The aim of these databases is to find availible AM materials or AM machines that meet the specified requirements. A good aspect of these databases is that none of the search fields are required, this helps to find machines or material that fulfill at least the entered data (Senvol, 2016). Unfortunatly the databases does not cover the required characteristics when the use of AM is advantgeous and therefore traditional methods are not incorporated. Before using this search tool the user should have an understanding and knowledge when to use AM.

The machine search functionality uses the machine manufacturer, AM technology, material, build envelope and machine price as criteria to find matching machines. The material search functionality uses criteria like material supplier, material type, mechanical properties, material hardness, certifications, thermal and physical properties to find a suitable material. All criteria can be quantified in order to provide results, however users can also indicate a range what the value should be.


Machine Search

Machine Manufacturer (Optional)	All
Machine Model (Optional)	All
Additive Manufacturing Process (Optional)	
AM Process	All
Material Type (Optional)	
General Material Type	All
Specific Material Type	All
Minimum size of the build envelope (Optional):	
X-dimension (inches)	
Y-dimension (inches)	
Z-dimension (inches)	
Machine Price in USD (Optional)	
Less than $49,999	☑
$50,000 - $99,999	☑
$100,000 - $249,999	☑
$250,000 - $499,999	☑
$500,000 - $999,999	☑
Greater than $1,000,000	☑
Price not reported	☑

Clear Form

Submit

Figure 2.12. Senvol database input fields machine search *Source: Senvol (2016)*

2.3.3. Scientific development of knowledge

Several papers have been written on the subject of assessing the value of including AM into the production portfolio of companies.

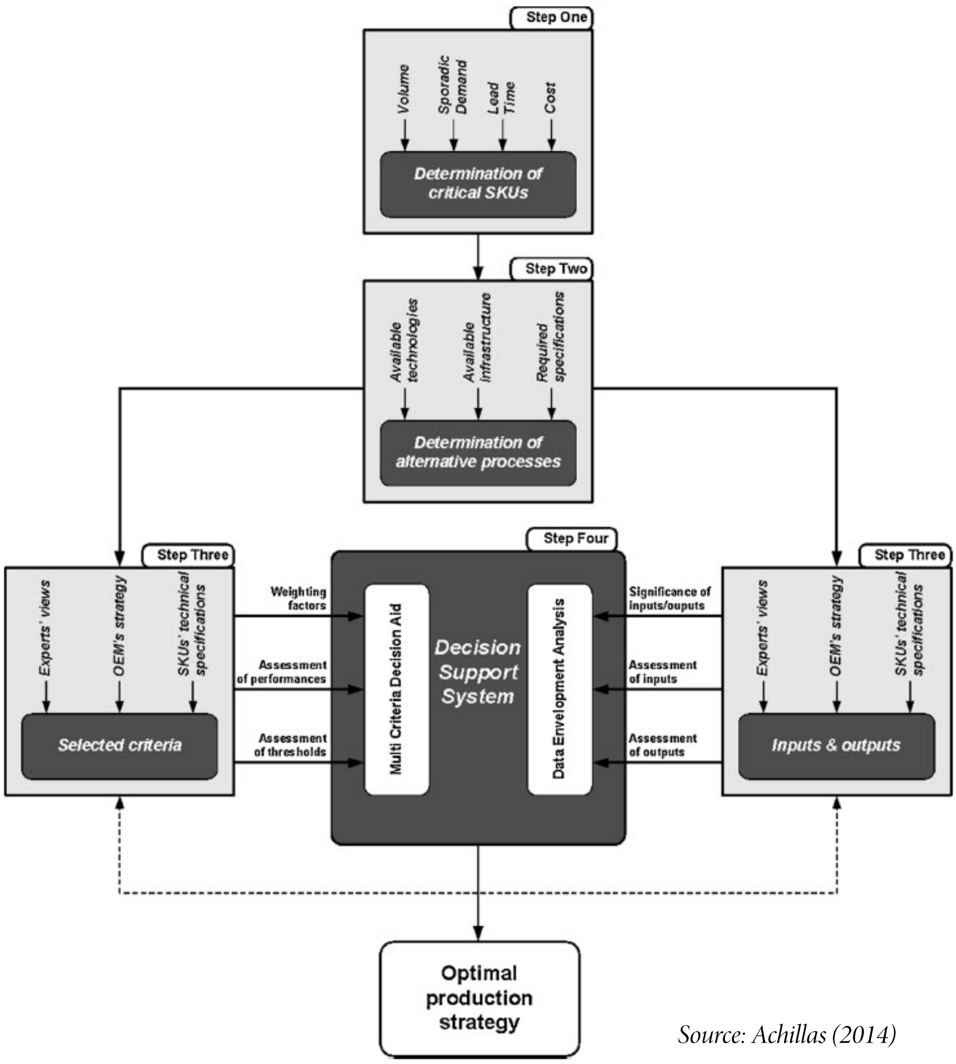
Decision making framework

Achillas et al. developed decision making framework using a combination of a multi-criteria decision making and data envelopment analysis for the selection of production strategies for AM and traditional manufacturing methods as well. The objective of the proposed framework is to provide a benchmark for AM and other traditional manufacturing methods and aims to identify an optimal production strategy (Achillas et al., 2014).

They selected a number of criteria including production costs, lead time and quality, and traditional production characteristics to assess AM technologies. In the framework the aim is on highest level senior management at manufacturing companies that are considering possible new production technologies. Their approach consists of four steps (shown in Figure 2.13).

1. In the first step products are selected that possibly benefit from a new emerging manufacturing technology. Based on the current challenges of the manufacturer in terms of the significance to the manufacturing operation like customer satisfaction,

production costs, the demand volume, the frequency of product demand, costs of material, technical specifications and production requirements the analysis of products is justified.
2. The second step in the decision making framework is to find alternative production methodologies. They suggest all production alternatives have to be assessed by different criteria including the ability to meet the product requirements and the current infrastructure. Achillas (2014) also includes the indirect use of AM as a hybrid manufacturing alternative. When all product requirements can be met, the capabilities of the current infrastructure, the availability of skills inside the company, production capacity and the consistency of delivering customer value have to be considered.
3. In step three, after possible alternatives have been selected the process is divided into two directions. Both directions require information from external experts and internal managers to develop a list of quantitative and qualitative selection criteria and weighting factors.
4. In the last step the criteria are ranked with a multi criteria decision tool and the inputs and outputs are analysed via data envelopment methodology. After the methods are executed, a final sensitivity analysis is performed to inspect the analysis.



Source: Achillas (2014)

Figure 2.13. Decision making framework

Implementation framework
Mellor et al. developed an AM implementation framework to structure the adoption of a new potentially disruptive manufacturing technology. The framework focusses on the organisation as a whole with an operation management perspective.
Mellor et al. considers both the internal strategy and external factors which can initiate the implementation of AM. According to Mellor et al. the implementation process is influenced by five factors namely, strategic, technological, organisational, operational and supply chain factors (Mellor, Hao, & Zhang, 2014). All factors are described below:

- **Strategic factors** should ensure a strategic alignment between business, manufacturing and R&D. Market and product characteristics drive often the investment decisions for strategic use of the AM technology. The technology benefits should be linked to the required capabilities of the business unit.
- **Technological factors** are linked to the business strategy to make use of the technological benefits. This requires a thorough understanding of the trade-offs for new manufacturing technologies. Knowledge of the advantages and possible barriers should create awareness in organisations adoption decisions.
- **Organisational factors** related to the structure of the organisation are influential in the implementation process. The size of the organisation, the required skills and expertise are important factors. Implementing AM without organisational change may result in high difficulties.
- **Operational factors** describe the impact on the product design. Due to the different characteristics of AM new design tools and methodologies are required to develop products with this new manufacturing method. Besides product design, the implementation of AM will also have impact on the production planning and quality control.
- **Supply chain factors** involves the relationships with suppliers and the customers. Mellor et al. (2014) proposes that AM requires an enhanced cooperation between the organisation and the suppliers as an important factor of the implementation success. Distributed manufacturing is a changing factor in the supply chain that requires attention.

Lindemann
Christian Lindemann, Reiher, Jahnke, & Koch (2015) developed a methodology to find appropriate parts that benefit from the use of AM. The method focusses to estimate the technical and economic implications. The method is aimed at organisations without AM knowledge willing to reduce the effort in order to find parts applicable for AM. A secondary goal of the methodology is to define a redesign approach which supports the identification of main functions of the product related to the context.
Lindemann et al. (2015) proposes a workshop in which requirements structured are gathered in order to select a part appropriate for AM. With this methodology inexperienced users will be able to identify feasible parts. The methodology is also suited for experienced users when the first steps of the workshop are skipped. The tool is flexible and can be used by different industries because is enables user to enable to change ratings of criteria. The methodology is divided in three phases; 1) information phase, 2) assessment phase, 3) Decision phase.

1. The information phase provides a basic understanding of the capabilities of AM. It shows the users the advantages and the limitations of AM. At the end of the first phase the user selects parts without the help of expert users.
2. In the assessment phase the collected parts are further analysed. With the use of a trade-off matrix the most potential AM parts will be ranked and selected. This matrix

structures the collection of information efforts. Different criteria are used in the trade-off matrix:

a. Part dimensions,
b. Part classification which includes complexity, buy-to-fly ratio and the necessity for post processing.
c. Material considerations (consumption and applicability)
d. Specific geometric conditions and property improvements
e. Processing time, including pre- and additional post processing time.

After this assessment all parts are ranked and the results should be discussed with experts. In the last section of the assessment, experts perform an additional analysis which covers the following four categories: material change, material consumption, processing time and economic aspects.

3. The decision phase finds the parts that benefit the most from AM technology. The user is required to collect and enter more specific part requirements with the help of a template. The results are summarized and other requirements are collected to hand this brief over to the engineer who will make a redesign.

Comparison of current methodologies

To evaluate the capabilities of the above described methodologies a comparison has been made to identify possible improvements. Table 2.4 shows a table in which the assessment methodologies are listed and analysed based on their functionalities. The goal of this research is to capture the features which are suitable and usable inside Capgemini and the AIE. In this analysis the specific capabilities and difference will be investigated. Overall the tool should ensure that Capgemini consultants have the expertise to find appropriate AM applications and construct appropriate business cases. In the most ideal situation the process is suitable for the clients of Capgemini with various backgrounds and levels of knowledge. The characteristics the methodology should have are:

- Suitable for multiple perspectives
- Give insight and provide an introduction in the capabilities of AM
- Mention the possible consequences and impact of AM
- Structures the data need, knows when what information is needed
- Should include traditional manufacturing, indirect and post processing methods
- Users should be able to adjust the data to their situation and make their own assumptions to determine possible future scenarios
- Is based on a database with AM knowledge

Criteria	Selling knowledge and expertise			Selling resources			Developing knowledge		
Availability of attributes, functionality or capability	Stratasys	EOS	Berenschot	Materialise	Rapidprototyping.nl	Senvol	Achillas	Mellor	Lindemann
Covering most AM benefits	✓	✗	✓	✗	✗	✗	–	✓	✓
Multi-level perspective	✓	✗	✓	✗	✗	✗	✓	✓	✓
Multiple levels of knowledge	✓	✓	✗	✗	✗	✗	✓	✗	✓
Ease of use (amount of effort)	✗	○	✗	✓	✓	✓	✗	✗	✓
Speed of process lead time Fast lead times	✗	✗	✗	✓	✓	✓	✗	○	✗
Mention possible barriers and consequences	✓	✗	–	✗	✗	✗	✗	✓	–
Transparency	○	✓	○	✗	✗	✓	✓	–	○
Traditional manufacturing comparison	✓	✗	✗	✗	✓	✗	✓	✗	✗
No technical knowledge is required	✓	✗	✓	✓	–	✗	✗	✗	✓
Introduction to AM	✓	✓	✗	✗	✗	✗	○	✗	✓
Ability to change assumptions to create growth scenarios	–	✗	–	✗	✗	✗	–	✗	✓
Technical feasibility analysis	✓	✓	✓	✗	–	–	✓	✗	✓
Economic feasibility analysis	✓	✓	✓	✗	✗	✗	✗	✗	✓
Interactive /visual	✗	✗	✗	✓	✓	✓	✗	✗	✗
Assisted by database	–	✗	✗	✓	✓	✓	✗	✗	✗
Structures and guides in information collection	–	✗	✓	✓	✓	✓	–	✗	✓

✓ Yes, – partially, ✗ no , ○ unknown

Table 2.4. Comparison of analysed assessment methodologies

Assessing the appropriateness of AM can be done in multiple ways, consultants are broader in their approach in contrast to the web based tools, which have a narrower scope. However, the web based tools provide the user with fast insight based on the most important criteria. This makes them directly limited in their use and it does not allow to incorporate special requirements or use cases. Scientific methods more suited for multiple perspectives and various knowledge levels. Table 2.5 gives a short overview of the general differences between the analysed methodologies.

Goal	Benefits	Drawbacks
Selling resources	Give fast insight, Interactive, Assisted by a database, Structures the information collection, Not complex in use.	Have only one perspective, Does not introduce AM technology, Expects that the user has knowledge, Has limited scope.
Selling knowledge and expertise	Perform a technical feasibility assessment, Often they consider the economics, Provide an introduction to AM.	Lengthy processes, Experts are needed, Most knowledge remains at consultants.
Developing knowledge	Multiple perspectives, Covers the most AM benefits.	Throughout expert knowledge is needed, Not interactive, user has to perform tedious tasks.

Table 2.5. High level overview of the methodology capabilities

All of the analysed methodologies have a focus towards AM and most of them neglect the use of traditional methods as a feasible alternative. However, sometimes conventional technologies can be more feasible than AM. The assessment methodologies do neither mention the effects of the indirect or post processing methods for AM extensively.
The goal of each methodology varies in perspective, some do only focus on prototyping and others describe the whole lifecycle. A few of the methodologies give the user insight in the possibilities outside the perspective of AM and show conventional alternatives. Some of the analysed tools enable stakeholders with different perspectives like business managers or engineers in the assessment. As discussed earlier, different stakeholders should be involved in the assessment because Capgemini has clients with various backgrounds. These stakeholders have different levels of knowledge. The type and depth of knowledge is different at each stage of the assessment process. In the initial stage, which is more strategic and exploratory of nature a different type of knowledge is needed than when the engineer starts designing the part. The type and depth of knowledge should be known at each stage of the assessment process. To assess the applicability of AM, multiple levels of knowledge are required. The methodology must ensure that all stakeholders are on the same level of knowledge and share a common understanding.

A general limitation of all existing assessment methodologies is that they are not build on the basis of a knowledge base which is constantly updated according to the latest insights in the industry. Knowledge bases and decision support systems have to be analysed to identify how to structure and present relevant data at each stage of the assessment process. Some tools structure the collection of information which is a welcome feature in these complex assessments. Constantly searching for (the same) industry specific data is unnecessary effort, users should only know what information to collect from their internal databases. This ensures that the used data cannot become obsolete easily. There is a need for a flexible and interactive tool. When such functionalities were presented simpler in the current methodologies, the differences and consequences of the choices can be better understood, allowing a choice based on an educated guess rather than information from the media or other wrong or outdated information.

In the most described methodologies users are not able to choose or change the data. Users are not able to change the assumptions, they are reliant on the data the tool offers. None of analysed methodologies enables the user to create growth scenario or sensitivity analysis, although this can make the tool more suitable for the future. Through the investigation of the developed systems the following shortcomings were identified:

- Lacking material selection or considering material aspects,
- Expert knowledge is not really shared and stored in a central database,
- Some methodologies do not integrate indirect and post processing methods,
- Most system lacked transparency and do not provide insight in the back end of the processes,
- Systems did not provide a reason why and how decisions are made,
- Although there were outcomes, users are not able to adjust the ranking and change assumptions to check whether other parts maybe are more feasible.

2.4. The use of decision support systems in the assessment

In order to conduct a research on the development of a DSS, first the theory of DSS should be known. This section investigates how the AM decision support system could be supported with knowledge-based application. In that respect, in this section, the theory is presented and the relevance of DSS will be investigated for use in the assessment. Secondly, potential benefits and drawbacks are reviewed to obtain insight in the pitfalls of developing a DSS. Followed by an explanation of the different types of DSS and the different components are described. Finally, methods for developing DSS are investigated.

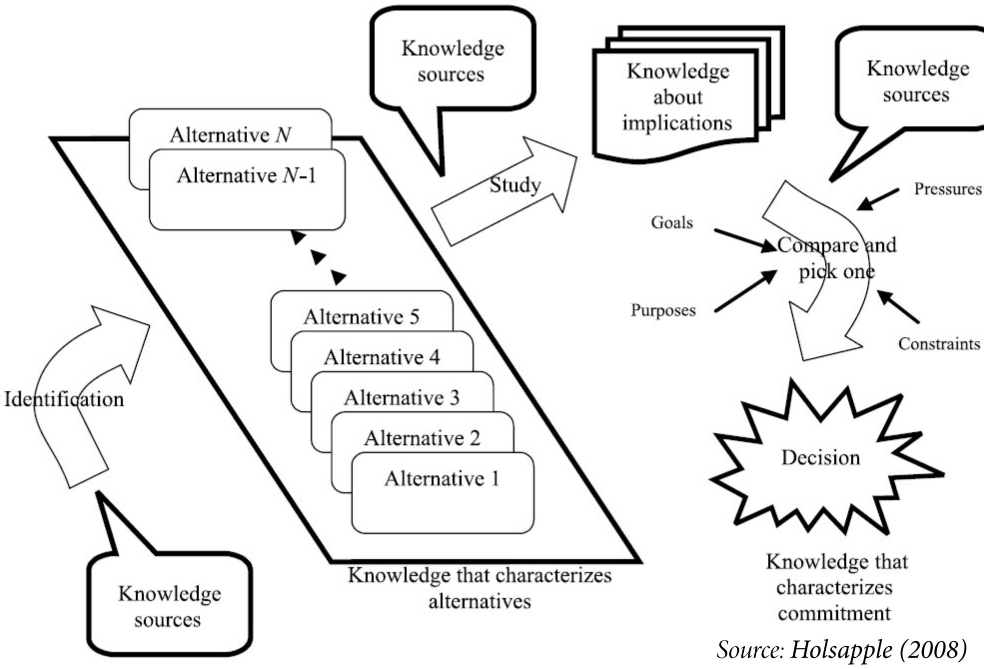
2.4.1. Decision making in a uncertain and complex environment

Developing DSS requires an understanding of decisions and decision making. Decisions are choices about alternative activities to reach desired goals (Simon, 1960). The decision making process is more than making choices, it covers also the activities from identifying the problem, gathering knowledge, generating alternatives and evaluating the alternatives on the basis of a number of criteria (Holsapple, 2008). The decision making process starts with identification of the problem, then alternatives are generated that can help decision makers improve the constraints. Subsequently, alternatives are evaluated by various criteria and the best alternative is chosen.

Decision making is a knowledge intensive activity (Holsapple & Whinston, 1996). During the decision making process new knowledge is created and not only the decision itself but also additional knowledge like alternatives with their possible impacts. This information seems not relevant right now but it can improve future decisions. Figure 2.14 explains a knowledge based decision making process.

In an ideal world the decision maker should have all knowledge to create all possible alternatives. In these situations the decision makers knows exactly the implications of each alternative and is able to compare the alternatives in relation to the criteria. This situation can never be realised in the manufacturing industry because:

- Users do not have all knowledge
- All alternatives might not be known to decision makers
- Users might not been able to find other alternatives due to cognitive limits and existing uncertainties (Simon, 1957).



Source: Holsapple (2008)

Figure 2.14. Scheme of a knowledge-based decision making process

In highly complex environments like the AM industry the decision alternatives will evolve fast and thus it is hard to reach a good decision. Turban (1995) divides decisions into three types: structured, semi-structured and unstructured. A typical example of unstructured decision is when not all aspects, information or criteria relevant to decision are known (Holsapple, 2008). Assessments require judgement and insight in the problem from the decision maker and due to this complexity these decisions are unstructured. Supporting the process of unstructured decisions with a DSS can assist in the discovery of knowledge to select and evaluate the most fitting alternatives. The cognitive capacities of people are insufficient to evaluate cause and effect relations due to the number of variables and interdependent relationships (Bennet & Bennet, 2008).

Decision making methods

Rarely is a situation completely unique. Different approaches are identified that can help in not completely unique situations. One approach to develop a DSS is to enable simulating the process of an expert. In this program the decision maker is provided with a set of questions specific to the situation. Another approach is to provide a program that provides insight in the decision making process by reviewing documents and examining what has been concluded. A last approach is to develop an environment which is specifically designed to provide decision makers with an atmosphere that positively influences the decision making process. The key to support unstructured decisions is to understand the role that individual experience or expertise plays in the decision to allow for flexible approaches (Louw, 2002). Structuring the decision-making process is required to address the complexity. Simon (1960) described a decision making process with four defined phases. The four decision-making phases are: intelligence, design, choice and implementation.

- **The intelligence phase** is used to simplify and make informed assumptions about the problem in order to understand the situation and correctly define the potential problems and opportunities. This stage involves searching for criteria that required in the decisions,

- **The design phase** involves the selection of a suitable model to analyse the decision and find potential alternatives,
- **The choice phase** focuses on using algorithms to solve the model and find the solutions from the decision alternatives. A course of action is selected from available alternatives.
- **The implementation phase** verifies the performance of the obtained solution. It involves adapting the selected course of action to the decision situation like problem solving or exploiting opportunities.

2.4.2. Overview of DSS

Decision support systems (DSS) are computer-based solutions to support complex decision making and problem solving. Through the use of such a system decision makers are able to find solutions to various problems. Typically the aim of these systems is to improve the efficiency of the decision making process, and indirectly improve the effectiveness of the decisions made (Pearson, 1995). Bosse & Jonker (2005) shows that in constrained settings (i.e. a defined domain and an accurate user profile preference) a decision support systems can improve the process.

DSS can support managers in making strategic decisions by presenting information and interpretations of various alternatives. Pal and Palmer identified three approaches in the development of current DSS: rule-based reasoning, case based reasoning and a combination of both (Pal & Palmer, 2000).

Furthermore, some DSS enable exploration of situations that do not yet exist. Analysing such situations require abstract models of reality. This modelling capability is important in DSS and enables lower costs of experimentation and shortens the time evaluating (Turban, 1995).

Advantages

A DSS structures the process and a well-developed process might result in decisions made in a shorter time and with less costs (Pick, 2008). DSS increases the understanding of the decision making domain what may lead to better decisions as well.

Over time Holsapple and other researchers reviewed the literature and identified potential benefits of DSS (Holsapple & Sena, 2005; Holsapple & Whinston, 1996). The summarized list is shown below.

- Enhancing decision makers ability to process knowledge,
- Reduce the time and costs needed for decision making,
- Improve the reliability of the decision process or outcomes,
- Stimulate exploration or discovery by decision maker,
- Reveal and stimulate new approaches to thinking about a problem or decision context,
- Improves the communication between decision makers,
- Provide evidence to support decisions or confirmations of existing assumptions,
- Better coping with complex decision situations (many alternatives, different consequences, various criteria),
- Create a competitive advantage over competing organisations.

These benefits depend on the context and the type of DSS. A DSS cannot provide all these benefits at the same time.

Drawbacks

However, current DSS have different drawbacks. Making decisions with a DSS does not necessarily result in better outcomes. Turban and Aronson mentions quality risks and maintenance risks as potential risks in DSS (Turban & Aronson, 2000).

- **Quality risks** are caused by using inappropriate tools for the development of DSS, generating wrong answers due to badly design or implementation of the DSS and poor data analysis.
- **Maintenance risks** are caused by future developments which require modifications to the system. When new information is not entered in the systems, the decisions are quickly outdated. The information in DSS in highly changing environments is never stable. For a new technology like AM current knowledge quickly becomes outdated.

Current DSS systems ignore the fact that human decision making often does not follow a logical path. People are not aware what they actually want and do not know the means to get there. In other words their preferences adapt during the decision making process (Payne, Bettman, & Schkade, 1999). The most systems do not allow the user to enter underlying values and do not support the reflection process needed for people to assess their values and preferences. Most DSS are analytical tools for high complex environments and it focusses on domain experts as users (Bellucci & Zeleznikow, 2006). The users' needs understanding why certain question are asked, and the rationale behind the model creates the output used for to create the output. With a well-designed DSS these risks and drawbacks can be avoided. Decision makers should keep in mind that user judgement is still required after the DSS provided an answer.

2.4.3. Different types of DSS

To define a good approach in developing a DSS an overview of the different types of DSS is reviewed. Power (2001) organised the DSS types in five categories; communication-driven, data-driven, document-driven, model-driven and knowledge-driven decision support systems. There are also hybrid DSS contain often a combination of the different categories. Some DSS are developed for specific purposes and others are more generic.

- **Data-driven DSS** focuses on easy access and manipulation of large databases of structured data. The most basic functionalities are search and retrieval. Examples of Data-driven DSS are simple file systems, data warehouse systems and business intelligence systems.
- **Model-driven DSS** are systems that include accounting, financial and optimisation models. These systems emphasize on the access and manipulation of a model. For example statistical and analysis tools are the primary functionalities. Analysis and optimisation models in this category are usually not data intensive. The data used in model-driven DSS are inserted by the decision-makers to support the analysis of the situation.
- **Document-driven DSS** supports users in finding and managing unstructured documents and webpages. The system integrates storage and processing to find and analyse documents. A search engine is a good example of a decision support tool.
- **Communication driven DSS** use ICT and networking technologies to support the collaboration and communication in group decision making process. A group decision support system (GDSS) is an interactive computer-based system to facilitate the collaboration of different stakeholders to identify problems and find solutions. Some examples of this category are video and audio conferencing.

- **Knowledge-driven DSS** provides recommendations for actions. Such systems are often called expert systems (ES) and contain specific knowledge of a particular domain. Specific problem-solving expertise in the form of facts, rules, procedures of a knowledge domain are stored in these systems. Knowledge-based DSS evolved in a new type of decision support known as intelligent decision support systems. The general DSS components are extended with ES capabilities like reasoning- and explanation components.

Other DSS

Web-based DSS are more and more used by organisations to aid in decision making of employees. With the advent of the internet new DSS applications were developed. Because of the rapid spreading of information, DSS and decision makers saw the advantages. The Semantic Web has created an increasing demand for methods and systems that can make use of imprecise information (Morente-Molinera, Wikstrom, Herrera-Viedma, & Carlsson, 2016).

Expert systems' (ES) main functionality is to provide expert advice in specialized situations. In contrast to a DSS which provides an environment to support the decision-maker to reach conclusions an ES makes inferences of already known information and comes to conclusions (Turban, 1995). Expert systems can deal with incomplete and uncertain information to reach conclusions and incorporates an explanation for its reasoning process. Expert knowledge needs to be captured and transferred to the computer system. This process consists of four activities knowledge acquisition, knowledge representation, knowledge inference and knowledge transfer (Turban & Aronson, 2000)

2.4.4. Components of DSS

DSS consists of three fundamental components; 1) a management system for the models and analytical tools, 2), a database management system which contains internal and external data, information or knowledge and 3) a user interface enabling the user to input interactive queries and to output graphing functionalities (Shim, Warkentin, Courtney, & Power, 2002). Carlsson & Turban (2002) mention a fourth optional component 4) the knowledge management system. This component can support the other components or act as independent component and provides knowledge to help finding solutions to a specific problems.

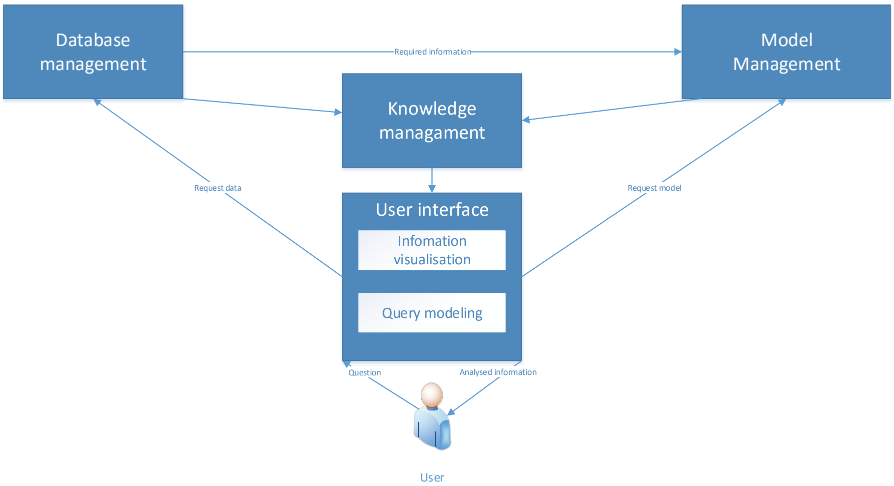


Figure 2.15. DSS architecture with knowledge base component

The model management

The model management subsystem contains abstract representations and functionalities (tables, mathematical formula etc.) needed to model the decision process and explain the relationships between variables of a particular problem (Drazan, 1995). A model is a simplified representation of reality and the use of models reduces the costs of experimentation, reduces time spent and improves the learning. Most models used in DSS are mathematical models that have a target output, a set of inputs, and operations for converting inputs to outputs (Liang, 1988).
The model management system includes and manages quantitative and qualitative models. Quantitative models provide the system's analytical capabilities. Qualitative models can be presented in terms of rules. Some models use a combination of qualitative and quantitative models and in some cases it is possible to transform the qualitative measures to quantitative measures by assigning values in a certain range (Turban, 1995).
DSSs can use different types of models. Turban assigns characteristics to DSS models and categorized it into seven groups (Turban, 1995) a summarize list is shown below:

Category	Description
Complete enumeration	A limited amount of alternatives are selected and modelled. The objective is to select the best alternative from a list of finite possibilities and assessing each ones impact.
Optimisation via algorithm	Although assumptions are often required an algorithm provides a relatively unbiased approach in solving the problem. The goal is to find the most suitable alternative from a large or infinite number of alternatives.
Optimisation via analytical formula	With a single formula the best solution can be found.
Simulation	Simulation is a technique for conducting experiments. By simulating different circumstances the behaviour of systems can be predicted. The objective is to select the best one amongst alternatives. When problems that needs to be solved are too complex for numerical optimisation techniques, simulation is often chosen. The decision maker may repeat the simulation multiple times with different inputs to define important variables.
Heuristic programming	Heuristics uses rules and available knowledge to find adequate solutions to complex problems. Most heuristic programs are characterized as self-learning or Artificial Intelligence (AI), the model improves the more knowledge is fed into the system.
Other descriptive models	Other descriptive models involve qualitative models expressed in terms of rules or formulas.
Prescriptive models	The goal of prescriptive models is to predict the future with scenarios. With this type of forecasting future values of variables can be predicted.

Source: (Turban 1995)

Table 2.6. Different types of DSS models

The logic, formulas and procedures in models can manipulate data elements in order to derive other data elements. To obtain these data elements external data sources can be used. When the models are well developed the model remain valid when the data changes (Mallach, 1994).

Scenarios

By using a model, DSSs emulate alternative courses of action for a given problem. Often these alternatives are called scenarios. Decision makers can adapt the scenario by changing values in the models as a result they see the consequences of the choices. Evaluating the outcomes enables to make quick iterations which leads to a right decision (Drazan, 1995). Scenario planning can be used in highly uncertain situations or the lack of seeing opportunities. In strategic planning, scenario building is often used to make decisions. Jarke, Bui, & Carroll (1998) mentions the use of scenarios can be effective due to the capability of stimulating thinking. Working with scenarios is an effective way of showing possible future states and is thus a good way of communication between stakeholders.

Database management

DSS uses multiple types of data stores (databases, sets of files) in order to provide relevant information in the decision making process. When relevant, the data can be used in the DSS. A DSS can contain data internally but also can information from external sources (Turban & Aronson, 2000).

Internal data sources refer to the databases and information systems that are available in the company. External databases refer to data sources outside the companies and are always maintained by other others. Many large external databases in the field of AM are accessible through the internet for example the Senvol databases.

Collecting data can be done manually or automated. The quality of the data needs to be validated to assure the integrity of the DSS. When data is not correct or the data does not exists a DSS may result in problems. Data can be organised using different types of models: relational-, hierarchical-, network- or object orientated- database.

The user interface

The user interface subsystem is an important component between the user and the DSS. It allows to combine the input of information, commands queries and models with the knowledge stored in the system. The interface determines how information is used and displayed. The style of language used and the type of dialogs, contribute to the ease of use the DSS. A well designed user interface uses terminology fitting to the decision maker and is flexible, consistent, simple and adaptable.

User interfaces enables to control the inputs and see direct result of the consequences. Graphics used in DSS are important because by visualising data and its relationships alternatives can be evaluated more efficiently. A graphical interface make changing values and variables more easily than a complex command line.

According to Turban (1993) the user interface should have some of the following capabilities: (this is an excerpt of the full list)

- Should speak the language of the decision-maker
- Capture, store and analyse user (dialog) queries to improve the system
- Present data in various formats and outputs
- Gives users assisting capabilities, flexible support
- Provide user interface with database and model base
- Stores input and output
- Provide training by example

- Provide flexibility to accommodate different problems and technologies

Furthermore a user interface should assure a correct use of the system and prevent entering incorrect data. When the user interface is poorly designed because of a too rigid or complex design no one will use the system (Drazan, 1995).

The knowledge base

The knowledge management base is an optional component and contains knowledge and expertise of a subject to provide explanations to non-expert decision makers. DSSs that uses a knowledge management base are called intelligent DSS or knowledge based DSS (Turban, 1995).

Knowledge databases contains descriptive, procedural and or reasoning knowledge (Holsapple & Sena, 2005). It provides information about the relationships between data and consists of rules that can constrain possible solutions as well as alternative solutions and methods for evaluating them.

Gathering expert knowledge is required to create a knowledge database. Usually, the expertise from a domain expert is captured and encoded into a computer program. Like with the database management component there are different ways to obtain knowledge these include manual, semi/automatic and automated acquisition (Turban, 1993).

The structure of the knowledge representation is important and affects the working principles of the whole DSS. Knowledge representation implies a systematic way of codifying knowledge from an expert in a particular domain (De Kock, 2005). Cohen & Feigenbaum (1982) proposed different types of knowledge representation schemes including rules, semantic networks, frames and cases. The forms of knowledge representation often used are:

- **Rules** are often in the form of if-then statements. When a condition is met, it causes or requires an action. After the knowledge is codified into rules it should be a simulation of the cognitive behaviour of human experts. Rules are easily readable, understandable and maintainable for a human expert.
- **Semantic networks** are a popular and easily understandable way of representing knowledge. In contrast to a fixed data structure, the knowledge is organised through nodes in a graph. The links between nodes describes the relationship between concepts. Most DSS and ES storing knowledge in a semantic web uses an inference component for reasoning. An inference engine is a mechanism that finds and executes rules corresponding with given input. The engine deduces facts and draws conclusions based on the inputs and the facts in the knowledge database which results in newly created knowledge (De Kock, 2005).
- **Frames** are structured sets of data with properties of an action or object. Frames are a variant of semantic networks only the information of an entity is stored in the concept itself: the frame. A frame consists of slots, each slot can contain information of the concept but it needs also be able to deal with uncertainty and missing values.
- **Cases** represents knowledge by using similar cases. It is a process that provides the solutions of previous cases to solve the current problem. The case methodology consists of two steps. First cases have to be found that solved comparable problems to the current problem, and secondly existing solutions need to be adapted to fit the current problem (Watson & Marir, 1994).

2.4.5. Developing a DSS

The goal of this research is to build a DSS that supports the assessment methodology. Therefore the development process of a DSS is investigated. There are a couple of factors that needs to be considered when designing a system. Mallach (1994) suggests some aspects that needs to be considered before the design of the system is started. The consideration factors are 1) The purpose of the system needs to be determined, this depends on the decision and the required outputs, 2) find external sources of data that can be used in the system, 3) Find and identify needed internal data sources and 4) understand all the important processes steps of the DSS.

Turban (1995) proposes a building process from the perspective of end users as a suitable way of developing. Eventually the DSS will be used by people who have different backgrounds and various perspectives on the AM domain. It is important to know the intentions, goals, objectives and expectations of the system users. The DSS development process of Turban consists of eight phases shown on Figure 2.16.

A. Planning: needs assessment, problem diagnosis and objectives of DSS,
B. Research: how to address user needs, investigation of resources,
C. Analysis: define the best development approach, define resources and models,
D. Design: consists of 4 components: user interface, model base, database and knowledge base,
E. Constructing: put together components,
F. Implementation: Test, evaluate and deploy,
G. Maintenance and documentation,
H. Adaptation: Continuously adapt and improve the system.

There are different development or implantation methodologies available all with different aims and starting point. In appendix 8.3 an overview can be found that elaborated more on the different DSS development methods.

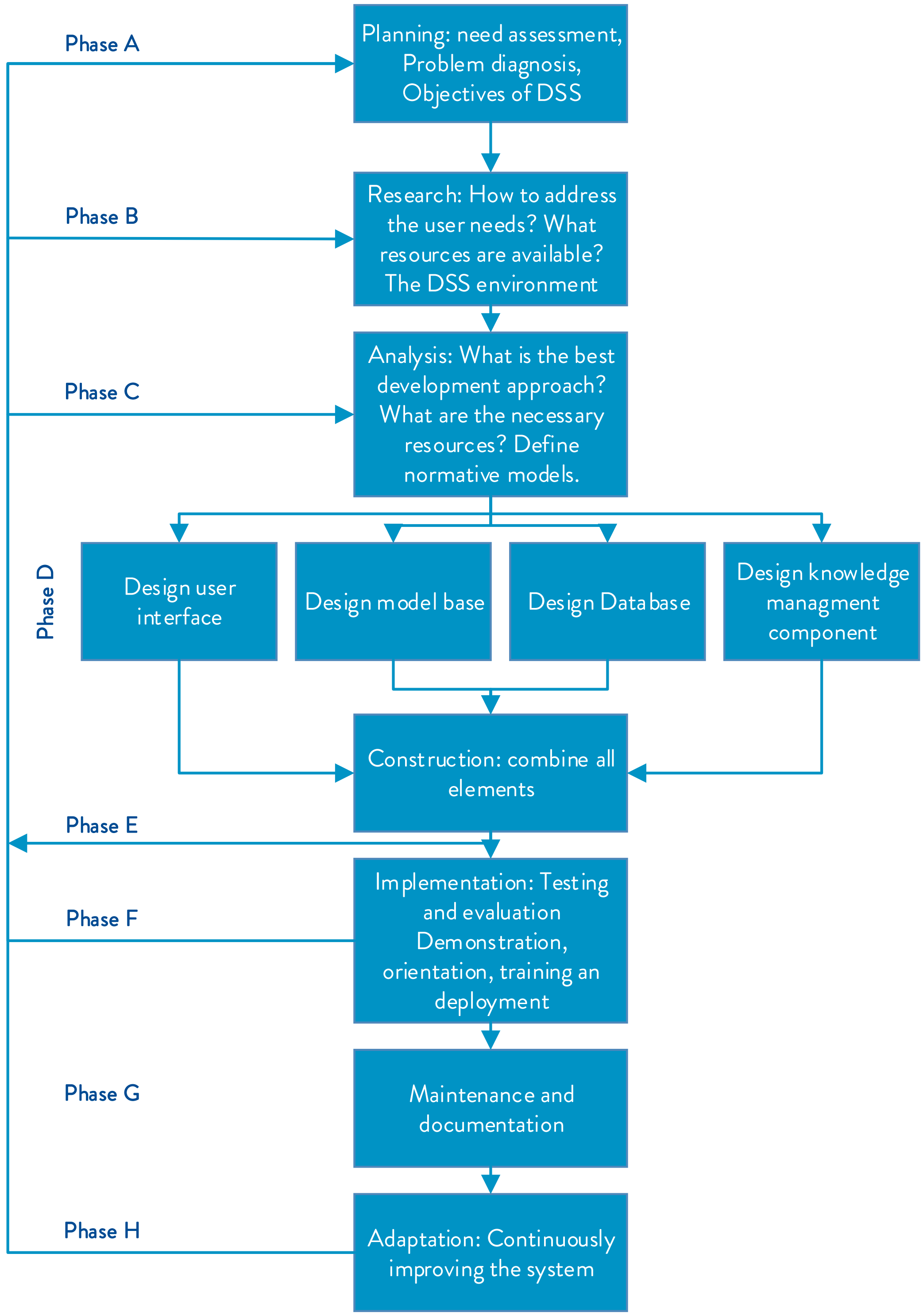


Figure 2.16. Phases of developing a DSS *Source: Turban (1995)*

2.5. Conclusion

The aim of the literature review was to investigate the field of additive manufacturing, current assessment methodologies and decision support systems. AM is currently at an inflection point, the technology is more and more used in the production of end-use parts. This trend caused an increase in the amount of companies evaluating possibilities and potential impacts of AM on their business. However, organisations still apply conventional ways of thinking to assess suitability of new manufacturing technologies. As a result, they are not capable of finding suitable applications. One of the causes is the lack of technology knowledge and understanding of its capabilities. Furthermore, the field of AM is complex and the technology has some specific characteristics which has to be incorporated in the evaluation for selecting the right production technology.

Currently, there are no sufficient tools available that assist manufacturing companies in assessing the value of AM to their company. With the development of an assessment methodology the use of AM can be stimulated by providing decision makers with a proper understanding of the technology and its capabilities in order to create an AM mindset. Finding appropriate applications does not only include the direct manufacturing of parts but the user should also assess the whole organisation and throughout all product life cycles. AM can be used in many different ways to enhance business operations, from the design phase (used for rapid prototyping) to the end of life stage where products have to be maintained sporadically. The AM technology offers also many advantages as an indirect method during the production of final parts, creating a hybrid manufacturing process where AM serves the traditional manufacturing processes.

Current web-based assessment tools aim at providing fast insight with a small amount of AM characteristics, but they often lack in-depth insight and do not all consider alternatives that might be more cost effective. In contrast in the recent years multiple consulting companies have started providing different types of services to provide a better understanding of AM and to find feasible AM applications. Consultancy service methodologies often require extensive knowledge from experts. In literature, AM assessment methodologies can be found, but these are not directly applicable to companies because they require extensive upfront knowledge.

A decision support system is proposed to assist in the complex and uncertain decision making. When assessing AM the advantages of the analysed methods can be integrated. It is shown because of mental constraints, manufacturers cannot find feasible applications. They usually use traditional considerations to identify alternatives. In addition, it is concluded that a DSS can help decision makers to identify more alternatives i.e. by providing them with better knowledge processing capabilities.

Different types of DSS have been found. Assumable, the best direction is to develop a combination of a model-driven and knowledge driven DSS to develop a hybrid DSS. The elements in these types corresponds best with the objectives of the assessment methodology. The DSS need to provide companies with proper recommendations of possible alternative paths they can follow concerning AM. Decision makers should be able to model different future scenarios and, based on the available domain knowledge, the process can be structured. Scenarios consist of qualitative requirements but during the process the specifications become more quantitative. The assessment methodology DSS should consist of four components, a user interface subsystem, a model database, a database and a knowledge database. All subsystems will ensure an easy to use but flexible method to identify the most suitable applications.

3. INITIAL DEVELOPMENT OF THE AM ASSESSMENT FRAMEWORK

3.1. Introduction

This chapter elaborates the development of the assessment methodology to determine the appropriateness of additive manufacturing in an organisation. Based on the literature review and analysis in the previous chapter the goal is to build an assessment methodology which is assisted by a DSS. The DSS development approach, described in section 2.3.5, will help to structure following chapters. This chapter describes the development path of the methodology process and DSS to assess the applicability of AM. With such a decision support tool, organisations are able to make AM related decisions more efficient and with a better output. The tool should assist in the process of identifying appropriate applications and feasible manufacturing methods. The ultimate goal is to find appropriate business cases which suits the needs of the businesses and uses the benefits and capabilities of AM.

The development of the methodology starts with phase A; an investigation of the needs, problems and objectives which the system has to fulfil. Research phase B, addresses the approach to these problems and needs. In phase C of the development the functionalities are chosen to fulfil those needs. The main functionalities are evaluated and the process is sequenced. In phase D the system is divided into four systems, user interface, model base, database and knowledge base. Afterwards in phase E, these systems are combined and tested. These last two phases can be read in chapter 4 and 5.

3.2. Phase A: Planning development

As described in the introduction, Capgemini wants to have more knowledge of AM to explain the technology to clients. Looking beyond this need, many clients of Capgemini are evaluating the technology and this requires knowledge to find appropriate applications. Beside these possible opportunities, clients want insight in the impact of the technology on their business. The introduction and literature studies described the need for a methodology that assist in the investigation of the applicability of AM. The purpose of such methodology is to efficiently asses the possibilities and impact of AM on the products and organisation.

Interviews

In order to obtain a better insight in the needs of Capgemini, several semi-structured interviews are conducted with account managers and department managers. These interviews helped to gain insight how Capgemini and her clients are evaluating AM. The client's needs are partly obtained by observations during client visits and by survey questions that are being asked in semi structured interviews. The interviews started with account managers and other employees that have a lot of insight in the company, their projects and goals.
In general, all the interviewees agreed with the findings from the literature that there is a need for such methodology. What role AM is specifically is going to play in the current offerings of Capgemini is unknown. When Capgemini is more involved in the strategic side of business, knowledge of a variety in technologies including AM is needed. During these processes AM knowledge is required. Currently, the consultants have an insufficient view of

the AM technology. Capgemini could assist in the strategy formulation whether it is wise to implement AM. This can help develop specific digital products where AM is a component. The clients of Capgemini have similar initiatives like the AIE to investigate new technologies but they are still viewing the technologies from the company perspective. Together with Capgemini they might be able to identify opportunities outside the perspective of the organisation. For now, Capgemini should focus on finding these opportunities for AM and create awareness. Some clients are conservative in the way they approach new technologies and most are sector is reluctant to implement AM. Multiple interviewees suggested that showing example case studies is an effective way to remove the bias towards new technologies. Capgemini could be seen as a system integrator where different software systems and processes can be integrated. The aim is not to enter the service market but the AIE can be positioned as a supporting partner that helps in the preliminary investigation of new services and applications for AM. By providing clients with insights how the technology might be used to increase the revenue or make the processes more efficient could result in new types of business opportunities for Capgemini.

Objectives

The methodology should serve as a means to identify appropriate business cases for AM by employees without extensive knowledge of AM. The methodology should make clear what clients could do with the technology and what the possible benefits are.
As analysed in the literature review, some current methodologies require extensive knowledge of AM, this challenge have to be solved by starting the assessment with an introduction to AM. The objective is to have the best of both worlds where the methodology is fast and interactive like the described web based tools aiming to sell resources and can provide structured knowledge from different perspectives, like the category aiming to sell their knowledge and expertise.

Problem diagnosis

Capgemini is willing to provide insight in the effective use of AM, but they do not have the tools or knowledge to be able to assess the appropriateness of AM for a company. The current web based tools do not provide sufficient insight and the other methodologies are lengthy and require highly technical knowledge. Tacit knowledge of AM is not present at Capgemini consultants but do want to provide this information to clients, to support the collective understanding of the technology. It is not the aim of Capgemini to offer consultancy services in the field of AM but Capgemini needs more knowledge to inform and create awareness to clients.

3.3. Phase B: Research

In order to address the problems described in previous section the methodology is developed on the knowledge gathered from the literature review, the analysis of the current methodologies and the interviews with consultants inside Capgemini. The requirements of a suitable methodology for Capgemini are described in this phase.
Developing such an assessment method requires a good understanding of the field of AM but also its impact on the organisations products. Even so, analysing the current consideration factors of companies is needed to obtain insight in the needs and during evaluations.
This section starts with an overview of the proposed framework describing the required inputs and outcomes. To determine the appropriateness of AM in a particular situation the process has to be divided in better manageable steps. As investigated in the literature

review the user should start with the business challenges. Even so, several benefits and limitations for using AM have to be incorporated in the beginning of the assessment. The organisation should consider the advantages but keep also the limitations clear to prevent surprises at the end. The most suitable manufacturing process should be selected according to the product specifications and sometimes these have to be simulated because in the early stages these unknown. Finally, the assessment should end with the technical and economic considerations whether the use of AM is appropriate and a business case can be build.

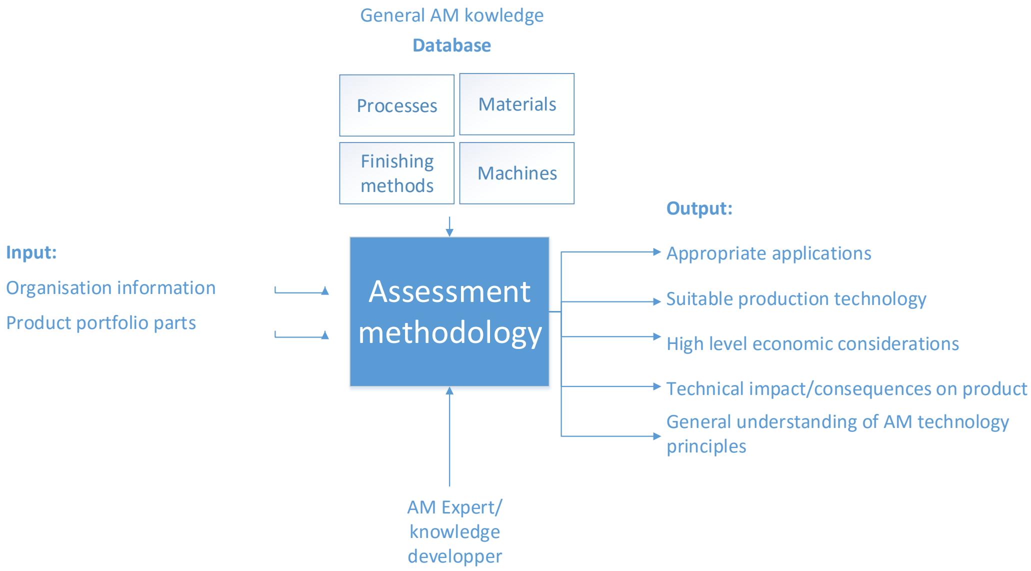


Figure 3.1. Black box overview of the proposed framework

Main requirements specifications

- The method should provide basic AM knowledge to construct a knowledge baseline,
- The methodology should structure the determination of appropriate applications for AM,
- The DSS should be understandable, easy to use and interactive to help organisations better understand the impact of factors on the decisions,
- The DSS should assist in the structured knowledge gathering and presents usable information at the right time in an understandable language for the user,
- The method should have the ability to temporary change and edit the values in the databases to influence the impact of certain factors on the final result,
- The methodology can give the underlying reasons why certain alternatives are more favourable.

Target group

The methodology to be developed, is focussed on companies who sell or produce products. Ultimately, these organisations should have physical products which can benefit from AM. For the service industry a different approach have to be developed to investigate possible suitable applications. Based on the current product portfolio, the assessment should be able to determine parts that could be redesigned to make full use of the AM benefits. Starting with the current situation is chosen because the product requirements and current challenges are known which will make the assessment more concrete and better understandable for high level business professionals.

Type decision to answer
In order to select the best fitting DSS the type of questions the system should handle have to be analysed. Most of the clients visiting the AIE have no clear vision on how to use AM, they read some articles in the media but the questions are often very broad formulated. During the process they have to be made more specific in order to select a clear focus for the assessment. During client visits to the AIE the questions organisation asked are collected and includes: "How can we use 3D printing in our processes?", "What is the impact of 3D printing on our product offerings?", "How can AM offer our customers with new added value?" and "How can we improve the time-to-market of our products?"

Resources for knowledge gathering
Every assessment is unique because the organisations and products differ every time. Besides the fact that the AM field is constantly changing, the basic principles remain mostly the same. Therefore these principles have to be translated by an expert for the use in the knowledge base. When the current situation of the AM field is modelled thoroughly and consistently the assessment methodology is flexible and can adapt to a multitude of situations. This external data requires constant updates by because the field is changing rapidly. Because the rapid developments in the field, fully static software is unsuitable. In order to ensure a flexible tool a web based tool is proposed. This makes it easier to ensure the tool contains always the up-to-date information without the need for manual updates. The DSS have to structure information based on the progress in the assessment by bringing together the knowledge in the AM domain and the internal available information.
Besides qualitative knowledge from experts, more quantitative information have to be integrated in the assessment. As can be seen in figure fFigure 3.21 different sets of information have to be integrated to draw conclusions. There are several online databases available (i.e. Senvol databases) which are updated regularly and can provide a quantitative perspective on the assessment.

Basic functionalities
In order to efficiently valuate the situation different factors have to be considered for an appropriateness assessment. At the same time these aspects should be the main functionalities of the methodology are shown in the following list:

- Create awareness and provide insight in the use of AM applications, benefits and disadvantages
- Enable guidance in the goal setting, set the direction for the assessment
- Identification of possible suitable parts to start with a possible pilot study
- Identification of possible production technologies including indirect processes, post processing and finishing methods.
- An analysis of the possible future economic considerations
- An analysis of the technical consequences

Scope
To structure the assessment in better manageable steps the process is divided in five levels. Due to the differences in the target group and the complexity of the assessment process the project focuses on multiple levels. The method should be flexible to be adjustable to a variety of situations. Each level should have its own structure and should have its own goals, activities, inputs and outputs.
The first level aims to create awareness and provide insight in the means to start considering AM. The second level evaluates potentially interesting parts to determine the suitability.

Subsequently, based on the requirements of the selected part a production methodology can be selected. When this technical information is known, the costs drivers have to be considered on a high level. In these early stages it is hard to do a fully economic feasibility analysis and it is not in the scope of Capgemini to offer these in-depth information. Although, the economics have to be incorporated to give a general indication of the economic considerations in the fourth level. With all this information the assessment can be finalized to show a summary of the decision process and give guidance in the follow up steps. For Capgemini it can be relevant to provide clients insight in partners that might to transform the business case in a product.
This thesis focuses on the levels 1 to 3 these are most interesting in terms of impact and relevance for Capgemini as well for the clients of Capgemini. Additionally the levels 2, 3 and 4 have the highest scientific relevance. The first level is required but in this thesis the main aim will not be on solely knowledge transfer but on the actual process of the assessment. The last level, level five, is also out of scope because Capgemini doesn't currently have a list of potential partners with the competences to do actual research and development or product development. However, the content of this level has to be mentioned in a high level to complete the assessment. Capgemini's role is more strategically identifying business opportunities that later will be handed over to external partners.
In this proposed process, clients who participate in innovation sessions of the AIE should be better able to identify opportunities in the field of AM specific to their company. Through the breakdown in levels the process can be seen as more accessible because organisations are now able to stop the assessment process if there are no sufficient reasons to continue.

3.4. Phase C: Analysis

There are several alternatives for the development of an assessment methodology, as identified in the literature study there are web-based tools, workshops with an academic background and consulting services. The aim is to provide a fast and interactive web based tool which is able to handle different perspectives and does provide multiple levels of knowledge like the scientific and consultancy services. The last two phases have resulted in the formulation of the following main objectives.

Main objective of the methodology

- Interactive and easy to use for the consultants of Capgemini,
- Division in levels to structure the process of knowledge gathering,
- Multi perspective based on the different perspectives an people involved
- Division in knowledge levels,
- Transparent decision making by showing rationale.

At each stage in the assessment process the user has to enter data and the system should return relevant knowledge. Every level the assessment goes a step deeper requires more knowledge and provides more specific information. Most decisions which are unstructured can be structured partially but are also fuzzy. In these cases the judgement and common sense of people is needed. In order to ensure the flexibility users are not forced to make decisions, all information presented gives an indication the rest depends on the judgement of the user. The process is guided by a consultant with sufficient knowledge of AM.

Preliminary information design

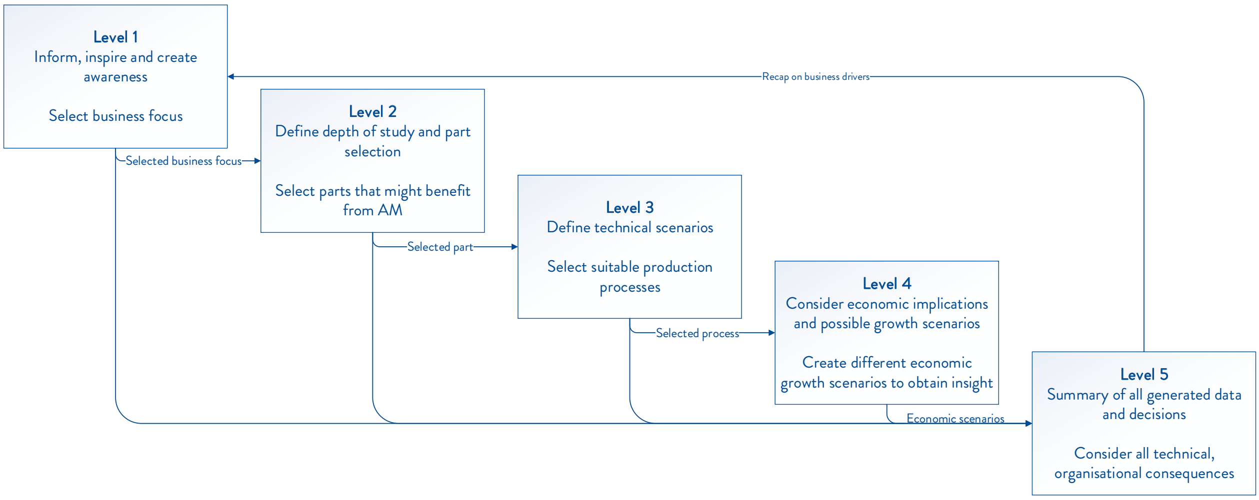


Figure 3.2. High level flow of information between levels

The requirements and objectives facilitated in the creation of the levelled structure. In total there are five levels that can be identified in the early phases of the identification of using AM. These levels are shown in figure 3.2 and have as goal: inspiration and awareness creation, opportunity identification, developing possible technical scenarios, assessing the economic considerations and finally next steps has to be defined. The contents of those levels are defined in more detail in the following sections.

Level 1 – Inspire, inform and create awareness

Inform and create awareness	Identify need and select development direction
- Basic AM characteristics are explained, - Trade-off compared to traditional manufacturing are shown.	- Business challenges are identified where AM can possibly provide a benefit, - Based on the challenge of the organisation the user should select the best fitting development direction.

Figure 3.3. Process steps in the first level, inspire, inform and create awareness

Understanding of the AM capabilities (design material, costs and properties) via a knowledge database is required to identify the best process-application match (Thomas et al., 2014). Therefore the first level provides an introductory knowledge of the AM industry, the AM capabilities and related technologies. This first level enables the decision maker to be better informed about the different possibilities of AM. Defining a baseline level is needed before starting analysing the applicability of AM, therefore it contains basic AM knowledge. This level aims to provide a new perspective on selecting a new AM technology to companies. Structured informing companies with new information is required to transfer AM knowledge and its characteristics.
When an organisation is interested in AM, they should always start with considering different business drivers. The reasons for choosing a business focus depend on several characteristics, namely: the state of the industry and the activities in the product life cycle and the goals the organisations chooses to accomplish. Where AM applies to the

organisation depend on many characteristics including the current business activities, product portfolio or predicted possible future scenarios. The goal of this level is to select an interesting primary business focus that complies with the organisation goals and the business environment. Analysing the current situation results in business challenges. Based on the challenges of the organisation a development direction is defined.
Selecting a primary business focus have to be done in close consultation with the client. As mentioned in section 3.2 from the user interviews the organisations visiting the AIE, their goals can be divided into three questions, 1) how can we earn more improve our customer offering to make more profit or obtain a higher margin (customer experience perspective), 2) how can we make our process more efficient to reduce the overall costs (operational excellence perspective) and 3) what could be possible new ways to create revenue and what new business model should be used? (New business model perspective)
Then, the next question is what they want to improve in the current situation. Hayes & Wheelwright (1984) suggested four ways of competing with manufacturing technologies in the market according to the competitive priorities: quality, delivery (Lead-time), cost and flexibility. These factors are part of the manufacturing strategy as the link between the market requirements and manufacturing. AM can offer in all four factors advantages to the competitive position of the organisation.
Combining both the competitive priorities and the perspectives of the adoption will result in insight of possible objectives. When the primary business focus are placed in a matrix, the business challenges can be mapped in each block. This makes it easier for users to identify the focus compared to the challenges of the organisation assessing the potential application. The matrix shown in figure 3.4 shows what AM can change. In the appendix there is a table with the benefits that describe each block.

	Competitive priorities			
Primary business focus matrix (Goal)	**Quality** Increased functionality, performance or quality	**Flexibility** Increased business flexibility and agility	**Time** Delivery improvement Time savings	**Cost** Improved financial Cost improvements
Customer experiences Create more revenue Product orriented	**Enhance product performance & functionality**	**Enable customer demand flexibility**	**Improve delivery speed**	**Reduce Total Cost of Ownership**
Operational excellence Improve process efficiency	**Improve process performance**	**Improve process flexibility**	**Reduce lead-time**	**Reduce process cost**
New business models Search for new models, create new revenu stream	**Develop new business performance capabilities**	**Enable new business flexibility**	**Enable rapid product introduction**	**Establish new cost structures**

Figure 3.4. Business focus matrix

Goals – The goal of the first level is twofold. First the decision maker should be provided with basic knowledge of the AM technology. An understanding of the current situation may help creating awareness for business drivers, capabilities and possible barriers of AM. Second the primary business focus have to be determined to set a goal for the assessment that solves current business challenges.

Activities - The main activity for this level is to provide the decision maker with a basic understanding of the AM technology. This includes explaining the general working principles and show the differences in technologies, processes and materials and characteristics. These principles are best explained by showing case studies and show what is possible and when AM can be advantageous. Moreover, insight in the technological benefits creates an understanding of the AM drivers to fulfil business challenges. At last the primary business drivers needs to be selected that meet the business challenges which potentially can be solved with the capabilities of AM.

Stakeholders – The people involved in this level of the analysis are the decision makers from the company, a facilitator with basic AM knowledge that is able to explain the technology with the help of the system.

Inputs – Although this level is static in structure, the process enables companies to identify business challenges that can be solved with AM. With this analysis the reason for adopting AM is investigated. Companies have to choose a business focus that can help them with these challenges and find specific AM applications in the organisation. This clarifies the reason why AM should be used.

Output – Finally, this level provides organisations with insight in the field of AM and awareness is created that can help them identifying applications suited for AM. Sufficient knowledge of high level opportunities, benefits and disadvantages are needed in the next level to identify the right parts that fit these capabilities. Proceeding to the next level requires a selected a primary business focus, this determines the type of questions asked and sets a goal for the total assessment.

Level 2 – Justification of development direction

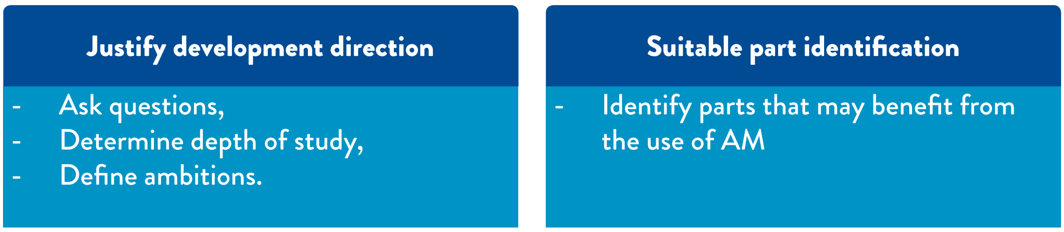


Figure 3.5. Level 2: justification of development direction and preliminary part selection.

Level 2 consist of two sub parts, first the selected development direction have to be justified and the depth of the study should be identified. The high level consequences have to determined, for example whether a company want to change some parts of their process or their products. By asking these type right questions the development direction can be justified. Secondly, suitable parts have to be found that may benefit from the use of AM.

Depth of study - Another important aspect to determine in the second level are the ambitions of the client with the assessment. Questions related to the ambitions should cover the depth of the study, identify in what degree change is accepted and what specific advantages can be used. This should clarify how the organisations are willing to use the technology, is it only used for niche markets? Or is this technology used besides their current manufacturing technologies? Besides that, the main focus of the company in the life cycle have to be integrated in the decision making because AM can have a profound impact and can enable change in the current processes.

Part selection – Based on the product characteristics potential parts are selected that may benefit from AM. The question should aim to identify possible parts worth assessing based on the selected goal. Parts with a high probability of meeting the characteristics of the primary business focus are selected. Looking beyond these characteristics is needed because sometimes it is possible to change current products to make them more suitable for AM. For example identification of critical components that are difficult or expensive to manufacture or parts that can benefit from the integration of specific AM functionalities. The part selection factors are based on the (non-expert) question from Lindemann (Christian Lindemann et al., 2015).
A tool can facilitate this decision making process. Based on the identification criteria, consultants are able to identify possible parts in the product portfolio that are able to meet the trade–off requirements. With this new mindset, the present gap between the technical capabilities present and the awareness the business has, can be closed.

Goals – The main goal of this level is to define the depth of study by asking the questions that helps organisations think about the scope and impact of decisions. In literature different characteristics have been defined to sort out parts at a high level based on criteria like: batch size, complexity, lead-time, current production costs and part size. Further it is important to identify important selection criteria for the organisation specific to the primary business focus like production costs, life cycle costs, lead time, quality or the enhanced product functionalities. Managing the expectations is needed to set reasonable goals.

Activities – Depending on the selected primary business driver the part selection criteria are adjusted. The part identification is a filtering process where the company should select parts based on a couple of criteria. Products have to be selected that fit best with the questions asked and criteria provided and can fulfil the selected development direction.

Stakeholders – This level is focussed on business or portfolio managers with little to none experience with AM.

Inputs – First, in what degree and depth AM is aimed to be used have to be analysed. These questions relate to the type of application and the impact of advantages in the product life cycle. This results in a list of potential advantages that can be used and the user has to select advantages are worth exploring. This selection gives a different set of requirements and question during the part selection, were parts have to be selected that meet the criteria. The part selection is divided in a quantitative and qualitative selection. For this the client have to provide a list of parts with basic part requirements like dimensions, lead time, quantity and manufacturing costs that may be considered for AM. With this approach existing parts are analysed if they can be redesigned. These criteria are used in the quantitative part selection and have to be adjusted until there are only a small amount of parts left. Subsequently, in the qualitative part complexities and AM specific capabilities (i.e. lightweight design and part consolidation) have to be assigned individually. Only changing the process is impossible therefore the analysis should consider potential changes in the design of the products.

Outputs - Results from the second level should contain a prioritization of parts that have a high potential for the use of AM. The most viable product including all information is transferred to level 3 to construct technical scenarios. When making a good decision alternative possibilities have to be assessed. Therefore comparing AM with other production technologies is needed. This includes the preconditions required for a specific end results like. Material consumption and processing times.

Level 3 – Technical scenario development

Product requirements modeling	Generate and select best fitting manufacturing method
- Enter requirements, - Make assumptions.	- Based on the technical requirements, current infrastructure and high level lifecycle costs the best fitting manufacturing solution can be found.

Figure 3.6. Level 3 technical scenario development

In level 3 alternatives are generated based on the product requirements. Generated options are prioritised according to the attractiveness of each possible solution. The technical feasibility defines whether the part can be made according to a small amount of requirements. An additional prioritisation factor should be a first (high level) indication of the costs.

Goals - The main goal of this level is to analyse possible manufacturing alternatives. Based on the technical requirements, the system generates some alternatives. The first selection is only focussed on meeting the technical requirements. All generated manufacturing alternatives can have additional benefits, like new functionalities but also possible limitations and constrains are identified for each scenario.

Activities - *Collecting requirements:* Based on the collected requirements a high level technical feasibility algorithms determines the prioritization of the best fitting manufacturing methods. This includes possible additional methods or the use of AM as an indirect manufacturing method or as a hybrid manufacturing technology. Comparing AM technologies with conventional manufacturing requires the collection of the part requirements.

Constructing a scenario: To develop a scenario, the requirements of the product have to be modelled. Some requirements have to be assumed to let the system find the best alternatives. An interactive interface should enable easy iteration between the input and the output.

Stakeholders – To define the scenarios based on the products requirements, extensive product knowledge is needed. Therefore organisations are required to integrate product portfolio experts in the process. The consultants need a technical background in order to critically evaluate the outcome of the algorithm.

Inputs – The third level requires modelling a scenario on the basis of technical requirements. The products are retrieved from the previous level and are enhanced with requirements in this level. Making a prioritized list requires making assumptions and modelling a scenario fitting the organisation's needs.

Output – The decision maker chooses at the end of this level a production process which is able to produce the modelled part most effectively. The decision maker is able to see directly the consequences of the decision. By doing so an AM mindset is created by informing the user with the capabilities of AM compared to traditional manufacturing.

Level 4 – Economic considerations

Figure 3.7. Level 4 Analaysis of economic considerations

Until now, the method selected a potential interesting product with a corresponding production process. The fourth level considers the economic implications of the selected direction to indicate the economics of the opportunity resulted from the previous levels. This estimates the possible economic impact in the current situation and a predicted future situation which gives insight in the possible changes of the main cost drivers.
A full economic feasibility analysis is a complex task because this requires lifecycle costing which should take into account many different perspectives. Predicting the economic benefit without a well-defined part can be hard to determine the economic impact. Additionally, these analyses are different every time and require expert knowledge.

Goals - The goal is to consider whether the economics are an improvement for the part by providing a thorough insight in the possible future economic consequences. Is the decision for the selected product and production methods economically wise and can it potentially result in a feasible business case. Through selecting possible economic future scenarios the decision maker should obtain insight in the major cost drivers for their part. The decision maker should be able to adjust the prediction scenarios and iteratively gain insight.

Inputs – Results and collected information from previous stages have to be used to define the initial cost calculation. Some additional business characteristics, like labour costs or overhead costs, are required that were not necessary for the selection of a manufacturing technology. Costs can be divided in five categories namely material, production, labour, machine costs and overhead costs. Also attention have to be paid to potential lifecycle costs, in some situations these costs can be better managed with AM.

Most production process related costs can be retrieved from the technical feasibility analysis (i.e. machine investment costs and other machine specifications). Other cost aspects that also have to be considered are the build speed, material costs, machine utilisation, build chamber effectiveness and defect rate. Assumptions have to be made because not all information is available in the system. In addition some assumptions dependent on the product or organisation which is assessing. The variables that have to be included in this analysis are shown in figure 3.8.

Output - At the end of the fourth level the decision maker has insight in the cost drivers and the future economic potential of the part. The economic considerations assessed the economic appropriateness of the end result.

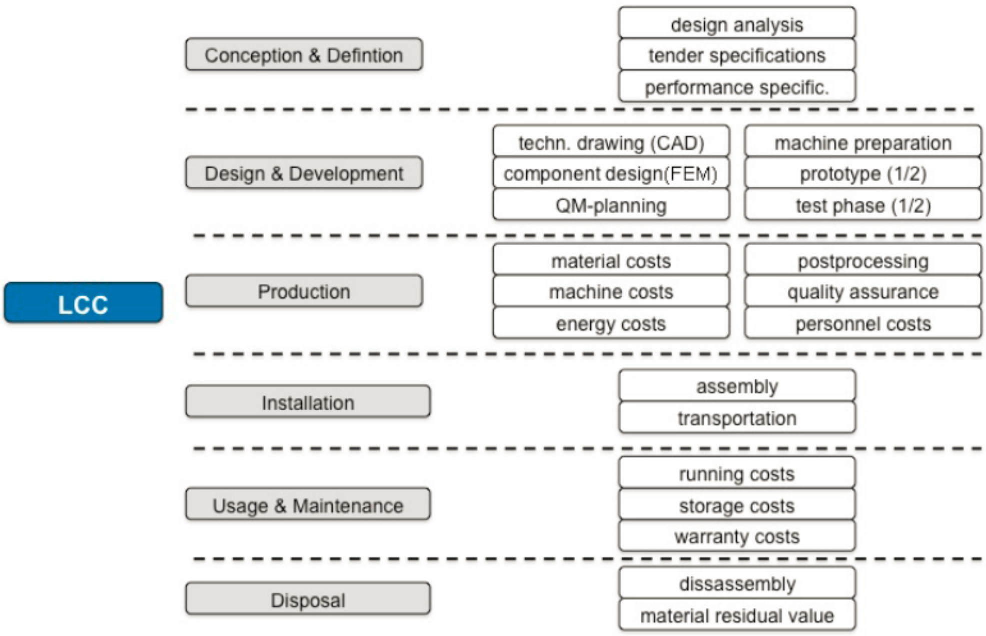


Figure 3.8. Different cost variables through the lifecycle costing model

Stakeholder -This process should be supported by an expert with sufficient technical knowledge of the manufacturing technology. To compare the outcomes an employee which is financially oriented have to provide a perspective on the current situation of the part is needed.

Level 5 – Action plan for product development

This is the final stage in which the decision maker is presented with a summary of the generated information. Which serves as a last analysis of the appropriateness of the development direction, product and processes. After the fifth level the technical capabilities can be further developed to give a better insight in the possibilities. This part is focussed on supporting the business professional in the next step in the product development process and show the relevant knowledge regarding design for AM, material selection, process selection, quality, safety and certification.

Goals – The aim of the fifth level is to provide an overview of the assessment process with the corresponding conclusions. An overview includes the rationale behind decisions, what alternatives were rejected and what assumptions have been made to come the conclusions. Also the selected goal in the first level needs to be reviewed. The overview can be used as a project briefing for the development of the selected product.

Activities – Level 5 requires the user to reflect on the assessment process and the primary business focus. An overview shows all relevant information of the assessment process and possible interesting information for the following steps that can help the engineers in the product development. Reflecting on the selected primary business focus is important to evaluate whether the result is able to meet the selected goal.

Inputs – All information collected during the assessment is used in the last level before the start of the product development. Technology and machine selection obtained from the technical feasibility analysis gives direction to product development.

Output - the result of the fifth level is a detailed briefing of development direction and a description of the business case which reflects on the chosen primary business focus. This briefing includes the rationale behind the decisions that are made in previous levels. A summary of all information can be collected to enable engineers to start working on the business case. Most important consequences for the product design and manufacturing are listed as well. Design guidelines are integrated in this level to provide a technical perspective on the product design possibilities. AM has also major impact in the production planning and quality control these aspects needs to be integrated to provide a complete overview. Other considerations that have to be integrated in the overview are:

- Quality indication,
- Print time, process time,
- Design rules for technology,
- Consequences for product development,
- Production planning and quality control.

The output of this level should give an overview of all next steps that the organisation has to perform in order to develop the business case. Providing an overview of the machine and material -suppliers landscape shows the relevant players in the field. Also recommendation needs to be drawn to ensure sufficient skills and knowledge to develop this business case otherwise they should consider contacting a design agency. At the end of this level Capgemini clients are helped in establishing relationships with third party AM part suppliers. In some cases, assistance is needed for the technology acquisition. Therefore it's important for Capgemini to develop relationships with the technology vendors in this industry to be able to provide a list of possible partners.

3.5. Conclusion

Capgemini aims to provide clients with a fast and high level insight in the possibilities of AM. Capgemini is willing to offer clients insight in an effective use of AM but they currently do not have the knowledge or tools to provide these services. Currently there are tools and methodologies available but they do not fulfil the demands. The consultants of Capgemini do not possess knowledge to efficiently asses the applicability. Therefore a methodology is proposed that helps them evaluate the effective use of AM for an organisation. In this way, the consultant is able to structured analyse the possible applications based on a knowledge database which contains the required information. The proposed methodologies always require assistance from AM experts but Capgemini do not want to provide engineering consultancy services. Therefore a middle ground must be found between the thoroughness of the current consulting services and the web based tools.

Based on these objectives a list of requirements and the main functionalities have been listed and are modelled as black box. To define the structure, the inputs and outputs for each function are described and placed in a logical order. This resulted in five different levels in which the knowledge gathering and presentation gradually increases. The structure of the methodology is designed to include flexibility but also to reduce the complexity of the decision making process, which makes it easier to modify the requirements and iteratively test multiple scenarios. The first level start by showing the capabilities and limits of AM to lay the foundations for selecting a primary business focus. In the second level suitable parts are identified and ranked based on the potential of meeting the selected goals. In the third level technical scenarios are modelled and the most potential production processes are selected. They are selected based on an algorithm that includes traditional and indirect manufacturing methods like, sand casting or other hybrid methods. Another aspect that is included are the post processing methods these have to be considered when aiming to use AM. Level 4 shows the economic considerations and enables modelling the possible economic scenarios. These scenarios can provide insight in future developments and the impact on the costs. Finally, in the last level 5, all decisions are collected and summarized in a complete overview. This information is a stepping stone to the next stage where the product can be developed.

4. CONCEPTUAL DESIGN AND IMPLEMENTATION

4.1. Introduction

In chapter 3 the methodology and DSS are described theoretically, in this chapter these theoretical concepts are elaborated into a DSS. The assessment process is formalised in a DSS and the working mechanisms are described. The system design and implementation are discussed in detail, and technical considerations are addressed. Since the methodology has to be translated into a web based tool a system architecture is developed to ensure all functionalities can be integrated. As discussed in the literature review the DSS consists of four components namely: a user interface, model base, database and a knowledge base. All these elements are discussed in section 4.3. Finally, the implementation of the methodology with the DSS is presented.

4.2. System architecture

The defined process structure, facilitates in the development of the DSS components. Each level in the methodology requires different tools and techniques to continue in the process. In chapter 3 the knowledge requirements are described per level, this chapter defines the origin or the creation of the required knowledge in the system. The DSS with all components is described in figure 4.1. The diagram presents the main function per level and shows the relation between the DSS components by indicating the information flows. This diagram also includes the required stakeholders and external databases.
Through this architecture iterations are possible and enable the user to flexible use the methodology. The interactivity should directly show the results of the input, in this way users should get a feeling of the impact of the values and the relations between concepts.

4.3. Phase D: DSS components and functionalities

This section continues on the DSS development process started in the previous chapter. All components and the relations, as specified in the system architecture, are described in detail. Finally, for each level, as mentioned in the phase C from last chapter, the components are discussed.

User interface
The internal data structures are important but the most crucial element in the DSS is the user interface. Through the user interface the decision maker is able to interact with the system and determines how information is displayed and used. With such interface the decision maker is able to navigate through the DSS. All the DSS components needs to be highly integrated in the user interface to enable the user to extract the right type of information that suits the user needs.

The DSS is not mend for analyse the situation once. Therefore the user interface has to support an iterative process. This enables to refine and enhance the insights the users can obtain form the system. The user interface should be transparent in the process it follows and the assumptions it used to come to a recommendation. If the users are not able to

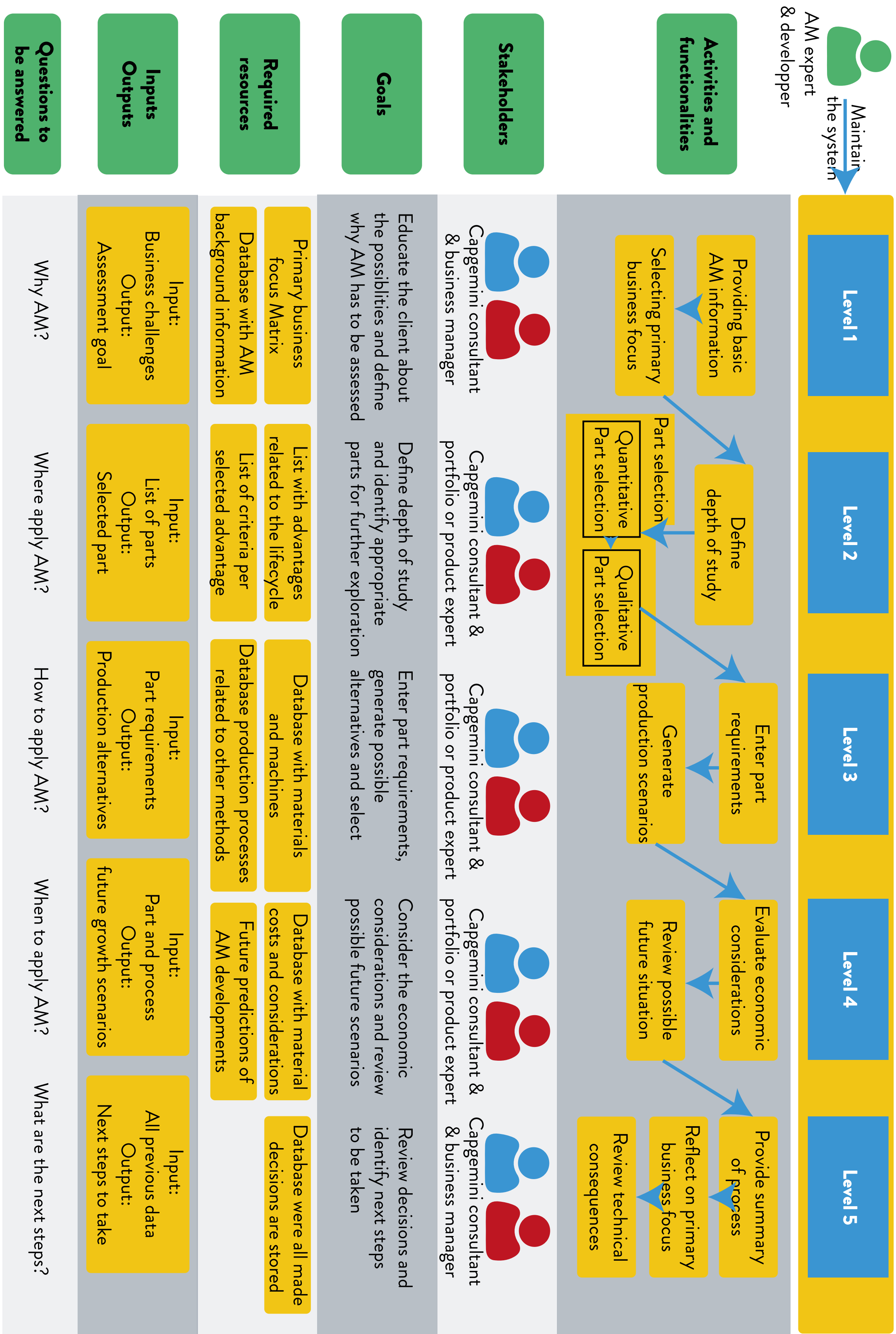


Figure 4.1. *System architecture of DSS*

follow the reasoning process the user may reject good alternatives because they have no understanding of the underlying principles. Another aspects are the dialog styles, these should fit the terminology of the user and will contribute to the ease of use of the system.

Model management system

For each level different type of models are needed, different suggestion and representation models have to be used in the system. In section 2.3.4 the different types of models are described. As stated before, a model is a simplified representation of reality. This subsystem manages all models and uses data which can be processed and interpreted as information. The DSS is based on mathematical formulas and logical relationships to provide recommendations. In the context of the DSS, different strategic models are used to support top management in the strategic planning. In order to explorer possible future situations the users should be allowed to manipulate the models to conduct scenario analysis.
Inputs are be obtained from a variety of sources such as external sources and future predictions in the form of quantitative and qualitative data. Qualitative data generally lacks high precision but it is useful in the early stage of the assessment. In the case of the development for qualitative terms, models are presented in rules. In some of the cases it is needed to transform qualitative into quantitative data by assigning values in a certain range. The functions of the model management system creates models by using building blocks from existing data.

Database

The creation of the DSS involves databases which contains raw data from diverse sources. These data elements are used in the models to generate recommendations. Each level has own requirements concerning the database and defines what type of data from what sources is needed. Most of the data required can be obtained from the internet, several services are available that provide industry data. Collecting the data could be done 1) on the basis of integrating external databases (i.e. Senvol material and machine database) or 2) data from internal databases could be retrieved and entered. Beside the external data, internal data has to be collected to provide recommendations specific to the user.
One of the challenges that have to be taken into account is the correctness of the data, when the system uses unreliable data sources the outcome will be uncertain. The data have to be structured to enable easy data retrieval. Some of the data can be stored in relational databases, this provides the DSS with greater flexibility in the data. However, some data elements are highly interrelated and for these cases a graph based database have to be used.

Knowledge base

The DSS should be equipped with a knowledge-based management subsystem because additional expertise is required to enhance the operation of the assessment methodology. As discussed in section 2.3.4, knowledge is defined as the link between the model and the database. This system supports the other subsystems to select and construct tools for recommendations. Knowledge determines the rules and conditions when they apply to a concept. A knowledge base contains the knowledge necessary for the understanding and provides rationale to augment the decision making process. Because the knowledge base emerges every day, experts need to help codify this knowledge into the system. The acquisition of expert knowledge is critical and involves collecting domain knowledge. Secondly, this knowledge has to be codified and incorporated in the DSS. There are two basic knowledge base elements, facts and heuristics.

4.4 Assessment process working principles

This section shows the working principles of the whole system. Examples are presented that explain how the appropriateness is identified and how the levels fit together. The examples show the flexibility of the tool and how it adapts for each situation. Relations between the levels are discussed to demonstrate the flow of the assessment. The described methodology is also used for validating the outcomes with Capgemini consultants.

Level 1 Inform and create awareness

The first level consist of five functionalities; an introduction, explaining the basic AM principles, show example case studies, provide basic technical information and selection of primary business focus.

Introduction

The DSS starts with an introduction screen to explain the intended use of the system and provides instructions to the users. These instructions ensure a proper use of the system and should make clear that the results provide an indication and still require human judgement.

Explanation of basic AM principles

Through the user interface the decision maker is introduced to the concept of AM. The system covers the basic principles in a Wikipedia-like environment and is rather static. Based on the rules and facts in the system, the knowledge base can provide the decision maker with the basic principles of AM. The model used in the first level to structure the data is descriptive of nature. Decision makers are structurally guided through the basic principles of AM. Additionally the database contains raw facts of information, collected from existing external data sources like Wohlers or Senvol.
In order to create a common understanding explaining the basic principles should start with the terminology and the generic AM process (shown in figure 4.2). The two most important things to explain are the fundamental layer-by-layer principle and that the geometry is obtained from a 3D CAD model. A video is used to explain these principles fully and entirely.

Figure 4.2. The first level explanation of the basic principles

Case studies of applications

During the interviews it is shown that showing case studies to clients is a good way to stimulate thinking and creating awareness. Based on the organisation interests and the industry the system shows interesting case studies. This functionality has be dynamic to show the most relevant cases. To realise this the knowledge base has to know what type of applications are relevant for what type of organisations. Figure 4.3 shows statically the part of the system where the decision makers can search through a database with possible case studies. A summarized version of eight cases is shown, more cases have to be added later.

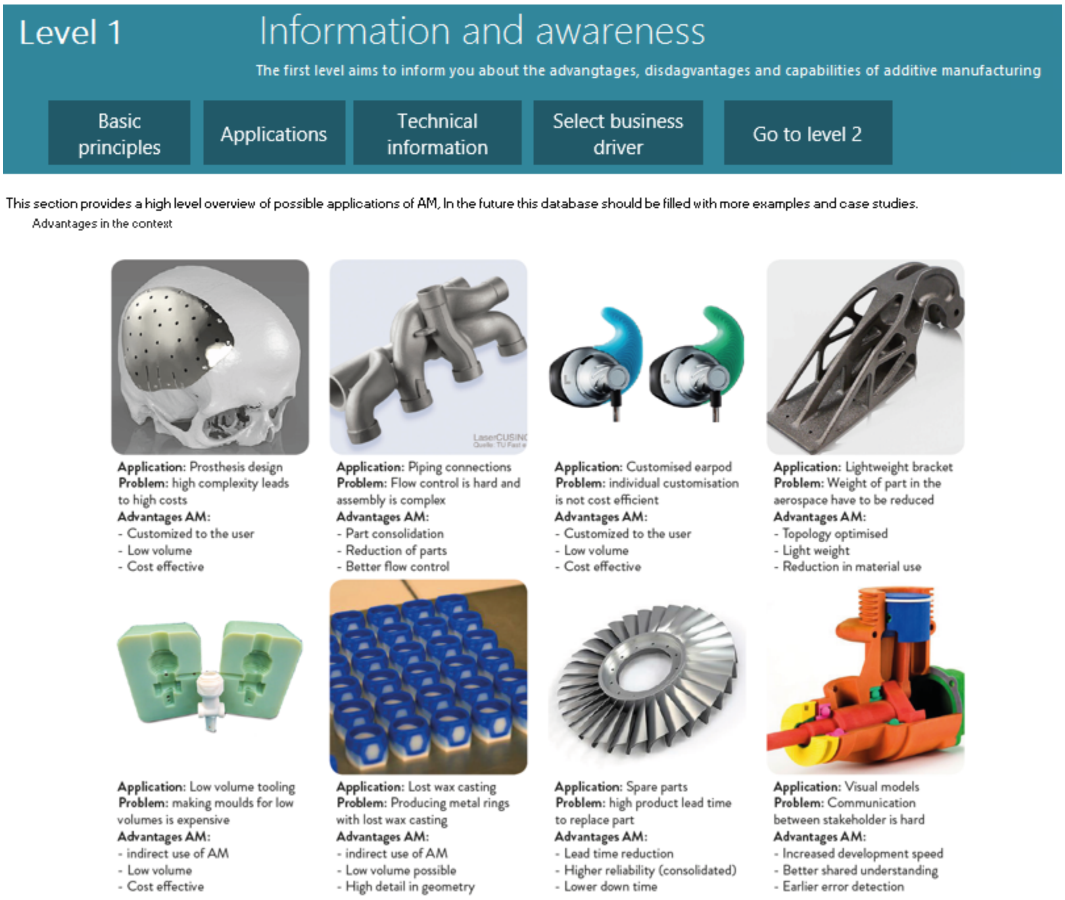


Figure 4.3. Application overview in level 1

Technical information

The database includes relevant information to explain AM to client who are not familiar with production technologies. Explaining the technical aspects of AM in more depth is needed to create a common understanding of the possibilities and impossibilities. Based on the classification of the ASTM the seven categories with the possible benefits are explained. Materials have to be addressed to show the possibilities, this has to be done with the remark because currently not many different materials are available. By describing the characteristics of AM compared to traditional methods the DSS provides a new perspective on the required capabilities. All this information does not have to be fully covered during the first level but can also be used as a reference point during the rest of the assessment. Figure 4.4 shows a screenshot of the interface for this functionality.

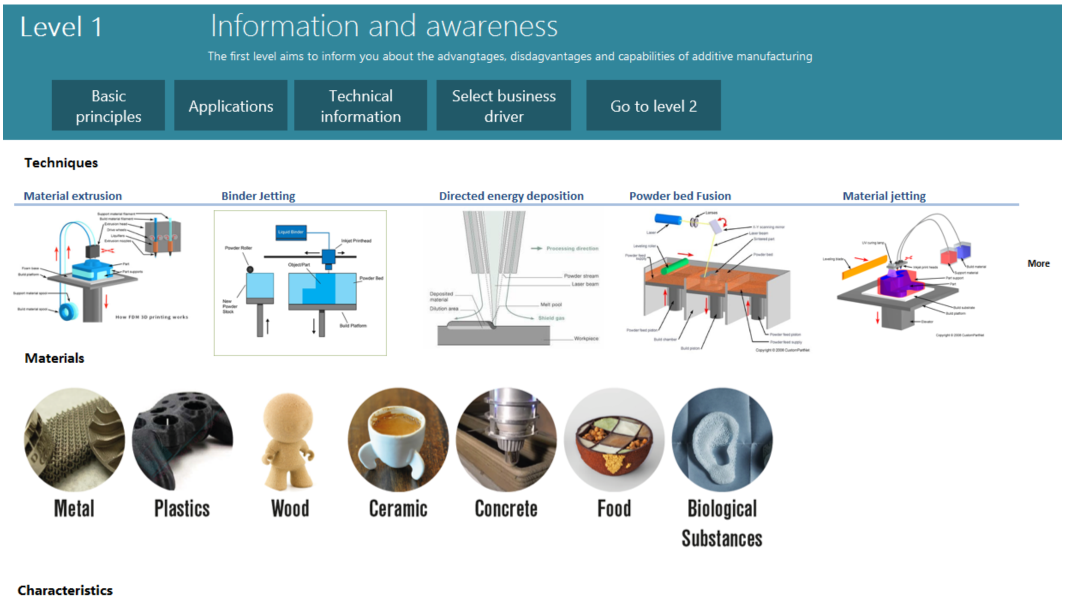


Figure 4.4. Level 1 technical information about AM

Selection of business driver
At the end of the first level the user has to select a primary business focus from the matrix. This matrix, shown in figure 3.4, consists of 12 fields and when a user hovers over a field it shows the challenges corresponding to the goal. For the business matrix the knowledge base uses a case based reasoning algorithm that shows which goals are related to which challenges. The database includes a list of possible business challenges in relation how they can be solved with AM. Decision maker can identify a primary business focus by critically reviewing the current challenges they face and want to know how AM can be used to solve these. Multiple challenges must match in order to select a potentially viable business focus. In appendix 8.5 the table shows the collected challenges mapped to the primary business focuses.

Level 2 depth of study and part selection

Level 2 has two functions, determining the depth of the use of AM and selecting a part that might be a candidate to redesign for AM and ultimately to identify a business case. This level aims narrow down a development direction and filtering out parts that have a low probability of meeting the selected primary business focus.

Step 1. Determining depth of study
The second level starts with determining the depth of study (shown in figure 4.5). This functionality examines what advantages are aimed to be used to solve the business focus. A database with advantages is linked to application types and stages in the lifecycle where they can be applied. Based on this selection, the range of possible benefits that can be obtained. The process is based on a descriptive model because the relation between the advantages and application types is determined based on cases. Depending on the primary business focus, advantages are dynamically filtered that provides the organisation with better insight in the possible direction of decisions. These insights should force the decision maker to think critically with what type of application have to be used and where in the lifecycle they should be applied. In this way the decision maker starts with ideating about possible benefits.

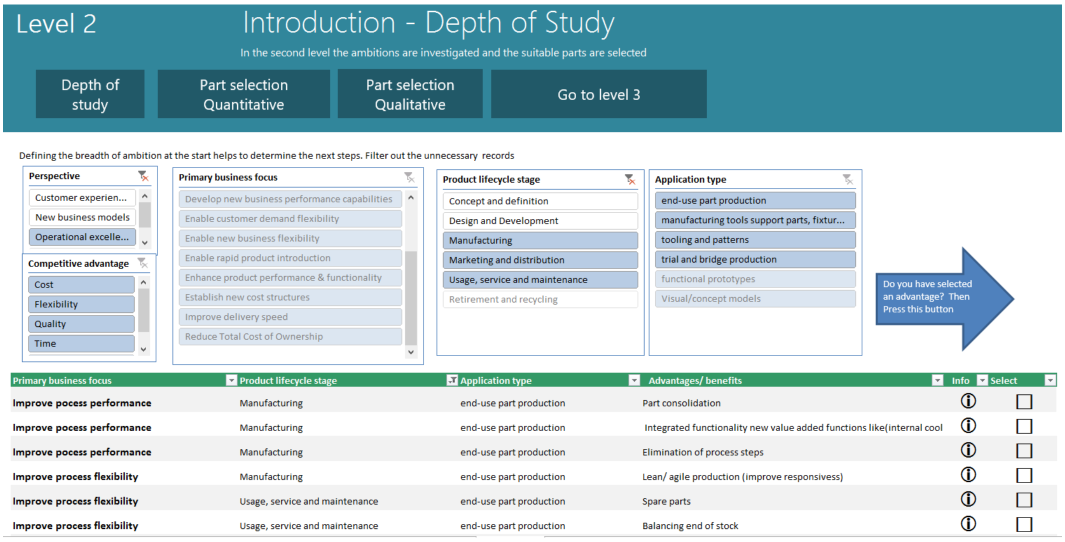


Figure 4.5. Depth of study level 2

Example: *When an organisation wants to improve their process performance and does not aim to improve the design and development or concept definition stage, AM can be used for the production of end-use products. As can be seen in figure 4.5 the remaining advantages are consolidating parts, integrating additional functionalities and the production of spare parts. The decision maker can now choose one or two advantages to explore where in the product portfolio the advantages can be applied.*

Step 2. Part selection

The part selection is done in two stages, a quantitative selection and a qualitative selection. Decision maker have to use their internal databases to select and import products and their characteristics in the system. Starting with a large list of parts that can benefit from the selected advantages the parts are filtered out until one part remains for further investigation. However this process can be repeated multiple time in order to assess multiple parts.

Step 2.1 Quantitative selection

The interface, shown in figure 4.6, for the part selection filters out inappropriate parts by a number of criteria. Starting with four general selection criteria about the current situation; quantity, lead time, dimensions and productions costs, the parts not meeting the threshold values of these criteria are rejected. Next, the advantage specific criteria have to filter out parts that do not meet threshold values. In the case of spare parts, the downtime costs and inventory costs have to be included in the selection. These minimum values are stored in the knowledge base and are determined based on existing case studies to ensure the remaining parts have an impact. The model used is an algorithmic optimisation model and rejects parts that have a low probability of not fulfilling the primary business focus.

Step 2.2 Qualitative selection

After the quantitative selection only a small amount of parts remain. In the second step, shown in figure 4.7, qualitative factors have to be assigned to the parts to assess what parts have the highest potential for AM. The decision makers have to assign complexity factors to the part for a future situation. Also potential AM specific advantages can be assigned to provide insight in other complexity factors.

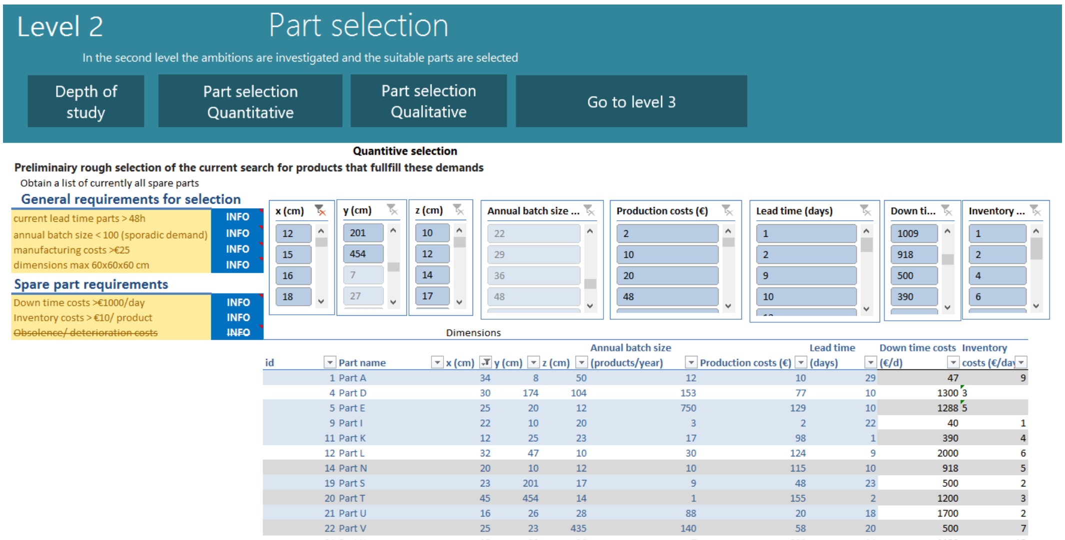


Figure 4.6. *Quantitative part selection in level 2*

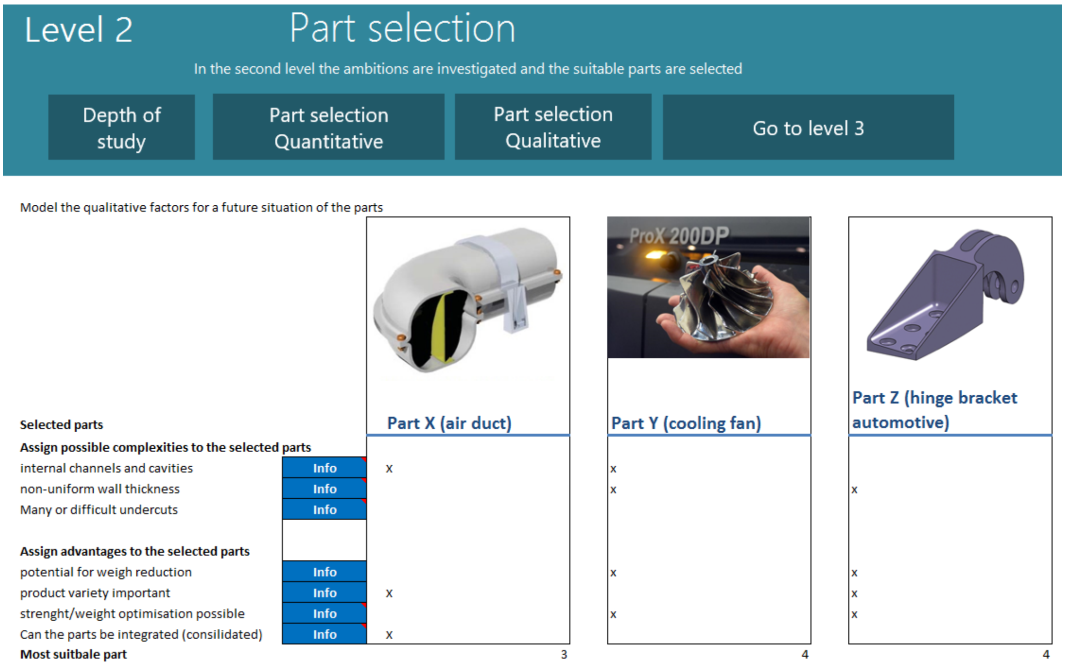


Figure 4.7. *Qualitative part selection in level 2*

Example: *An organisation provides a list with 30 parts of which they think can be used to improve their process performance by using AM for their spare part production. All parts are filtered out that are generally too large for the build space (larger than 600 mm), have low lead times (can be obtained between 48 hour), have low production costs (below €25) and have a sporadic demand (max 1000 per year). Three different types of parts remain in the analysis. The complexities (i.e. internal channels and cavities, non-uniform wall thicknesses and many or difficult undercuts) have to be evaluate if they can apply in a future product redesign. Subsequently, also the possible advantages have to be assigned. For example, is there a potential for weight reduction?, is product variety important? Or can the parts be consolidated? Parts with the most aspects assigned doesn't necessarily have to be the best solution. The final decision still requires human judgement.*

Level 3 technological scenario development

The third level finds the most appropriate manufacturing method for the selected part. Based on the collected part requirements an algorithm, shown in Figure 4.8, selects the manufacturing methodology with the highest similarity between the technical requirements and the process chain capabilities.

Step 1. Entering part requirements
The user interface of the third level, shown in figure 4.8, starts by showing a form in which the decision maker can further specify the requirements of the selected part from the previous level. Besides the already available data more specific requirements like: quality specification, geometric specifications and material needs to be provided. All additional product requirements are collected and stored in the database. The decision maker should obtain this data from their internal systems or by estimating the values.

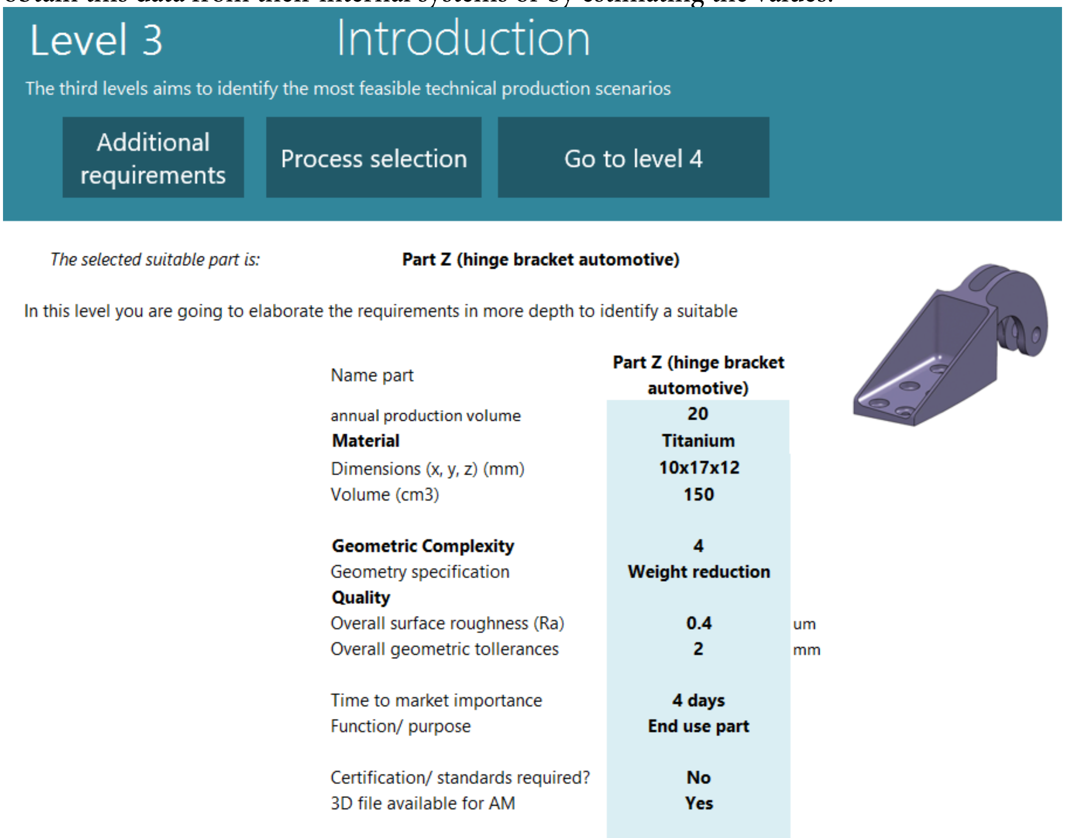
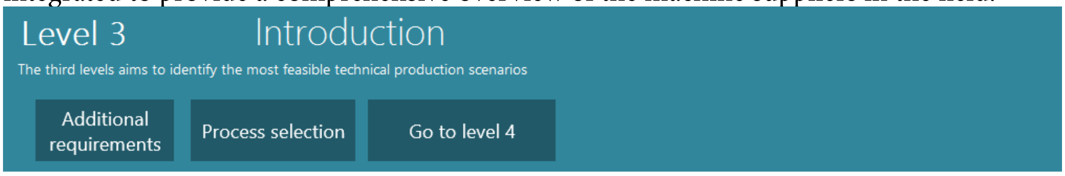


Figure 4.8. Entering part requirements in level 3

Step 2. Generate manufacturing scenarios
Based on the collected part requirements the interface shows different manufacturing scenarios. The role of the knowledge base is to relate the requirements of the production technology capabilities to the technical part requirements. The knowledge can be represented in a semantic graph which describes the relations between the requirements and capabilities. In order to select the best fitting technology the database contains information about production capabilities. External databases are used to collect this data, they contain information about material and machine suppliers. In case of a match between the requirements and capabilities, alternatives are generated. These matching values enable the system to calculate the similarity between manufacturing capabilities and the product

requirements resulting in a list of suitable production technologies. All this knowledge can be used to create a prioritized list that indicate the degree of suitability.
When the user adds requirements to the system, an algorithm should search for alternative production technologies that can meet all requirements. The system has to be responsive to directly show the new alternatives, in this way the decision maker can interactively learn from the impact of certain requirements have on the final product and process.
Whenever a requirement cannot be met with one manufacturing method, the system should search for additional (post) processing methods in order to meet a requirements. This functionality requires a relation between the manufacturing technology, the part and the additional process because these aspects determine the possibility. For example, the overall surface roughness of EBM method is not sufficient for the intended purpose therefore polishing is required but due the geometry (internal channels), this post processing technology is not an option. The knowledge components should contain information about condition when a relation can be made.
At last the model, shown in figure 4.10, differentiates between the production methodology and the machine. This level uses at first only production method characteristics which in general are used to generate alternatives. Later in the process, the machine capabilities are integrated to provide a comprehensive overview of the machine suppliers in the field.



		Most feasible production methods			
Processes	**Ranking**	**1**	2	3	3
Primary process		**SLM**	**CNC milling**	**Sand casting**	**EBM**
Secondary process		**Polishing**	-	**Wax mould printing**	**Sanding**
Functional					
Machine		**EOS XX.X**	**General CNC machine**	**EnvisionTec**	**Arcam**
Throughput capacity (products/day)	1	✓	✓	✓	✓
Dimensions (x, y, z) (mm)	10x17x12	✓	✓	✓	✓
Volume (cm3)	150	✓	✓	-	✓
		✓	✓	✓	✓
Complexity	5	✓	-	✓	✓
Material	Titanium	✓	✓	indirect possible	✓
Quality					
Overall surface roughness (Ra)	2	-	✓	✓	x
Overall geometric tollerances	0,1	✓	✓	✓	-
Certification/ standards required?	No	✓	✓	✓	✓
3D file available for AM	Yes	✓	-	✓	✓
current Lead time (time to market)	4 days	✓	✓	✓	✓
initial material costs estimation		€ 80	€ 125	€ 150	€ 95
Percentage similarity		10	9	9*	9*

Figure 4.9. Generated manufacturing scenarios

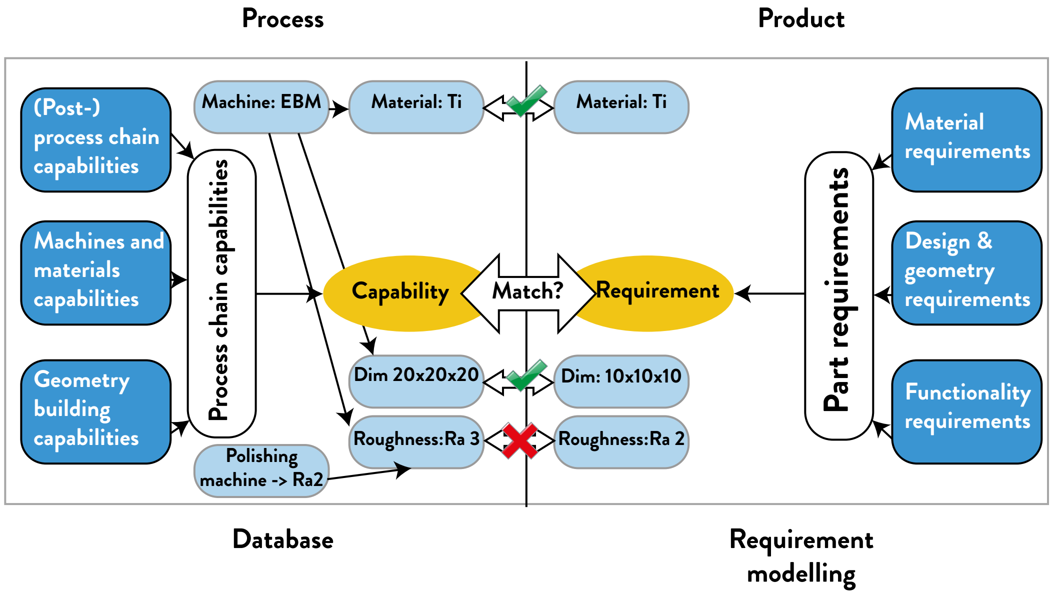


Figure 4.10. Relations between part requirements and process capabilities

Level 4 economic growth scenarios

The fourth level assesses the part with a financial perspective. Addressing the economic considerations at this point is important to provide the user with an overview of the possible economic implications when the decision is implemented now and in the future.

Step 1. Review economic considerations

As mentioned in the literature review, costs are often the decisive factor in the choice for a production method. In order to determine these cost considerations predictions for the material and machine prices should be known. Integrating lifecycle costs in this levels required a different approach, many of the required calculations have to be based on many assumptions. When using lifecycle costs does not make sense due the predicted little impact, organisations should focus on solely production costs. Exactly justifying these costs is hard because not all benefits can be translated into a monetary unit.

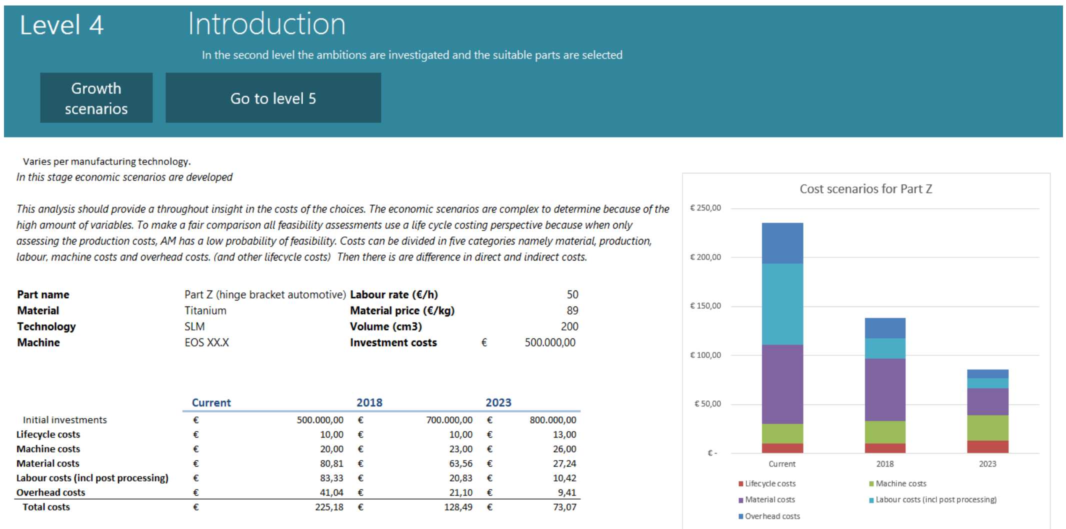


Figure 4.11. Growth scenarios user interface in level 4

Step 2 Analysis of future and growth scenarios
In order to model future scenarios the system needs a data set from an external party, like Wohlers, Senvol or Roland & Berger, to generate economic scenarios. Users have to analyse this data to obtain awareness of a possible future appropriateness. Such analyses requires information from all levels, and where needed information should be added in order to give a complete overview of the costs in the life cycle.
The costing model relates all gathered data points and incorporated it in to the costs calculation. When specific variables are unknown, the system is able to identify these and ask for facts or assumptions of the values that should be worked with. In contrast the database contains default values for variables, but the decision maker should be able to adjust them to meet there assumptions.

Level 5 summary and action plan

Recap of process
Summarizing and showing relevant data is the task of the knowledge base in the last level. The model in the fifth level ensures a complete overview of all steps in the process. It is able to summarize and shows the relevant aspects that can be used in the upcoming product development phase. A summary of all used data and related conclusions is retrieved from the knowledge base and shown to the user.

Technical consequences
Based on the model from the third and fourth level, new information can be presented that is only needed during the development stages. Usually that would be design guidelines and contact information to suppliers. Additionally, data is shown that is helpful for the users that further develop the product, for example design guidelines.

Possible partners
Recommending possible partners requires a list which state what partner can provide what resources. From the technical scenario analysis the system knows what type of machine has to be used and what skills are required. The system can refer decision maker to other parties that have more specific skills and knowledge with whom the results can be discussed.

4.4. Phase E: Implementation of the methodology

The methodology can be offered as a service besides the regular service offerings of the AIE. It can be used to create awareness and insight in the AM technology. When Capgemini is able to offer new insights to clients of these new technologies they will consider Capgemini faster for more strategically oriented projects.

When an organisation visits the AIE and expresses interest in AM during the presentations of the different technologies, a start can be made with this methodology to offer a high level AM appropriateness assessment. The first level can be used to provide more information and the primary business focus can be defined to give a direction to the assessment. A start can be made with the second level where possible advantages have to be selected to give further direction to the assessment. This will result in a list with criteria which has to be used to search for parts meeting these requirements. The list of parts is used in the next session to further assess for potential AM parts. In order to do this efficiently the organisation will have to provide Capgemini consultants with a list of possible parts. Before the next session the Capgemini consultants can analyse the parts and later explain their process to their clients.

During this session Capgemini consultant will have to ask for additional data therefore it is important that clients' portfolio or product managers are present at the sessions.

Using this methodology requires some training before it is used. Consultants willing to offer such services to their clients can learn the methodology but it is also important they have sufficient knowledge of the technology itself. Basically they should be able to explain AM without the first level of the methodology. Such theoretical background is needed to prevent wrong or imprecise statements.
The consultants will need to have technical knowledge to use this developed method inside Capgemini. When consultants have limited technical AM knowledge, this will limit the depth of the assessment. Therefore possible key partners with this technical knowledge are required. These parties are able to develop insight in the cost of AM in greater detail. The partners can extend the service offerings to create an innovative consultancy service which covers the most aspects of adopting AM.

4.4.1. Stakeholders and Responsibilities

Different stakeholders are relevant in this DSS environment. Hackathorn, Keen, & Sprague (1981) identified 5 roles which all operate on different aspects of the system. Multiple roles can be carried out by the same person. The roles are the following:

- **The manager or user (the client)** who is the decision maker and want to know whether AM is a suitable production technology for their organisation. This person is responsible for the supplying the correct information needed in the DSS.
- **The intermediary (the Capgemini consultant)** who is the person to change the parameters of the DSS or even to make suggestions for changing certain parameters.
- **The DSS builder or facilitator (AM expert and developer)** configures the DSS for direct use by the user or intermediary. This person assembles the capability of DSS and is somewhat familiar with the problem area.
- **The technical supporter (AM expert and developer)** develops new system capabilities and components for the DSS. These components may be new data sources, presentation formats and analysis models. This person has a strong familiarity with the technology used in the DSS.
- **The tool smith (DSS developer)** develops new technology, new hardware and software. It has a strong familiarity in developing and constructing new technology components.

A consultant from Capgemini can fulfil the role of the intermediary and the user ate the same time. Together with the client or independently before a meeting, a consultant can go through the DSS and present the result to clients to arouse interest. Although the system is designed to be easy to use the use of it might require a short training. The technical supporter can be an external partner of expert in the domain of AM. Furthermore the DSS has to be built by a programmer in collaboration with an AM expert.

The role of the consultant is crucial during the assessment methodology. The direction of the process is guided by the consultant and the quality of the outcome depend on the question asked during the sessions and the obtained information. It is important the consultant learns to work with the tool, in order to eliminate faulty advices. Besides that it remains important to have an in-depth insight in the field of AM and the basic principles.

The composition of the group is important. The further the level progresses, the more technical knowledge is required. In the most optimal way, a good assessment process requires a multi-disciplinary team with different background and management levels to construct consensus in the organisation.

4.4.2. Maintaining the system

Important to note is that the assessment is build based on the current situation. New applications are being introduced on a daily basis therefor the assessment and DSS should not be static but maintained regularly. The domain of AM is fast changing and every day new and improved machines are coming to the market. This requires at least a monthly update to keep the system and the recommendations up-to-date. Because the DSS is built on a web based platform the updates are instantly usable. The same applies to new scientific discoveries, new insights are process have maintained.

It is not desirable when consultants with little to none experience in AM are maintaining the system, this has to be done by people with a thorough understanding of the technology. Possibly, one person can be trained to perform these tasks. There should be a constant search for case studies and these have to be modelled in the system. The advantages and goals of these studies have to be related to the process of the methodology. Hard data of machines and material specifications (i.e. prices and capabilities) have to be retrieved from external databases. However, the relations between for example the post-processing methods and the production technologies have to be based on proven applications.

4.5. Conclusion

The conceptual design described in this chapter has shown how the assessment methodology works and how it have to be used.
The system architecture, shown in figure 4.1, provided the basis for this chapter. This diagram showed in general the relation between the components and the process which are further elaborated. The development of each DSS component has been extended and applied to the method. Showing the points of attention and what resources are required to ensure a well-integrated system. By explaining the working principles of the process and the transitions between each phase have been described and enriched with examples.

Level one is aimed to inform the user and create awareness. Though explaining the basic principles in a Wikipedia-like environment consultants are able to find all information they need to. At the end the goal of the assessment have to be selected in the matrix, this has to be done according to the challenges the organisation faces. The second level requires to narrow down the direction how the goals should be met by selecting specific advantages. Furthermore, level two requires two stages of filtering through the list of parts of the client. First the parts are filtered on the basis of quantitative requirement which rejects parts that do not meet the criteria needed to obtain advantage. Second, a qualitative selection has to be performed with the selection of parts. This includes identifying possible complexity factors of future parts and possible AM specific advantages that can be used.

In the third level the requirements of the remaining part are collected. With this information the system is able to find production technologies that are able to meet the requirements. Based on the algorithm a similarity factor between the part requirement and the production technology capability can be calculated to find possible matches. Level 4 identifies the economic considerations. Future predictions are integrated to provide a long term perspective of the future appropriateness of the part. Finally in the fifth level all collected information is combined a summarized to show the possible next steps to be taken in order to realise the decisions.

In order to implement this methodology inside Capgemini the methodology can be used in addition to the current technology presentations of the AIE. However consultants have to be trained to use the tool properly. Besides the methodology also technical expertise is required especially in the latter stages of the process. A training with more background information on AM will eliminate faulty statements and thus provide a realistic output.

For maintaining the system an AM expert have to constantly update the case studies in the system. This also includes defining new relationships between concepts through new insights that were not proven before. For the exact data like machine and material specification the tools has to rely on external database like Senvol.

Overall the developed methodology can be used for the validation in the next chapter to research in what degree these functionalities are really contributing to determining the appropriateness of AM.

5. RESEARCH VALIDATION

5.1. Introduction

This chapter describes the validation activities that were undertaken to assess the effectiveness, usability and relevancy of the assessment methodology. Methods that are used for validation and the findings from the validation are discussed.

5.2. Validation methodology

In order to validate the assessment methodology the objective set in chapter 1 have to be restated.

> *Develop an assessment methodology which is supported by a DSS to enable people with little knowledge of AM to present relevant information in each stage of the decision making process to determine the applicability of AM and indicate the value for further research into these areas.*

To validate whether the developed methodology can help consultants assess the appropriateness of AM efficiently two types of validations are conducted. During the development an evaluation session in the form of a user research is conducted which aimed to find flaws, misguided thinking tracks or faulty assumptions. Secondly, a more formal validation has been conducted to be able to answer the objective described above. These sessions were used to test in what degree consultants are able to use and understand the methodology.

To assess the validity of a model the developed prototype from chapter 4 is used. Numerous inconsistencies are corrected during the development of the model. The modelling process was an iterative process, feedback and new insights from literature or interviews were incorporated and lead to the desired outcome.
The prototype is built based on the system requirements. However, not all functionalities could be integrated, due to time and technical limitations. In general, the functionalities described in chapter 4 are mimicked as far as possible without influencing the user interactions. Many of the functionalities are hardcoded and displayed statically.

5.2.1. Prototype fidelity

In the early stages of software development low fidelity prototypes such as paper prototyping are useful because they are cheap and simple to produce. Besides being cheap and simple, modification of such prototypes is quick and easy and focusses on validation of high level aspects. However, to validate the methodology a possible paper prototype is not sufficient because it is not able to show the interactivity, show working functionalities and enable the user to explore the tool by themselves. In contrast, developing a high-fidelity prototype is more time consuming and more focussed on lower level details like interface issues. To resolve these issues a mixed-fidelity prototype is proposed.
The prototype is developed in Microsoft Excel, as described in chapter 4, because this program enables to make calculations and an interface can be built easily. The prototype is built based on the system requirements. However, not all functionalities could be integrated, due to time and technical limitations. In general, the functionalities described in chapter

4 are mimicked as far as possible without influencing the user interactions. Many of the functionalities are hardcoded and displayed statically.

5.2.2. Evaluation interviews

During the development different evaluation session were undertaken to perform a usability test. The objectives of the preliminary prototype are to evaluate if the DSS is consistent and correct. The validation of the model is considered as a check to see if the model is logically structured, usable and can be effectively used to assess possible AM opportunities.
Feedback from users is important to determine the applicability of the developed solution. In this study, the feedback from users was obtained using a semi-structured interview. This type was selected because it combines structural organization of the questions with flexibility. It gives the interviewer the possibility to explain interviewees the different aspects of the system and asking about their opinions.
A qualitative research approach is chosen to validate the objectives of this methodology because in the development stage many of the functionalities have to be developed in greater detail. To prevent excessive work by building inappropriate or unclear functionalities this evaluation aims to identify if the made decision are on the right track.

Prototype

To assess the validity of a model a preliminary version of developed prototype from chapter 4 is used. Numerous inconsistencies are corrected during the development of the model. The modelling process was an iterative process, feedback and new insights from literature or interviews were incorporated and lead to the desired outcome.
The prototype shows the functionalities of the proposed methodology and does include all details. The visuals are not developed in detail but provide guidance for using the method. It is not the goal of the prototype to be inclusive, but rather evaluate the methodology. The prototype DSS should allow the user to get an indication of a possible working procedure of the system. Each level is modelled statically and the researcher guides and explains the working principles to which the user can respond on. Building a complete working web based tool is time consuming and the real need for the functionality needs to be validated first. Developing all functionalities in full detail is unnecessary because the prototype mimics the concept and working principles of the concept.

Evaluation procedure

The evaluation sessions starts with explaining the goals of this tool and outline the process steps which the user has to follow. Besides that, the participant is asked to review the levels and the inputs that were needed to complete the level. Each interview takes on average one hour.
To investigate if the tools is usable and does what is intended to do, it is necessary to describe the expectations of the methodology. The tool is developed for the consultants of Capgemini, to see if it is useful a validation and evaluation study is done. However the prototype has to be checked by experts to identify potential inconsistencies in the process.
The validation process starts with a general explanation of the intended use and background of the tool. The researcher clarified the target group and the context in which the tool has to be used. Participants is explained that while they walk through the prototype and that they are free to comment on each aspect. They have to use the methodology and the DSS as a guideline. During the process the participants are guided by a researcher which asks questions and can clarify any ambiguities. The goals and the special point of interests are

mentioned. For example a point of attention is the structure of the tool and that the user has the right knowledge at the right time. After this general introduction each level is independently treated. The complete protocol for the evaluation can be found in appendix 8.6.1.

The result of this validation has to show if the working structure is correct, this includes 1) analysis whether the user has the right knowledge at the right time during the assessment, 2) Is the user able to effectively assess the appropriate use of AM? And 3) identification of possible bottlenecks.

Participants

Four one-on-one evaluation sessions are conducted. Two times with PhD students with a technical background which are highly informed about the AM subject and two times with Capgemini consultants who did not have a technical background. In each individual meeting the prototype is presented and step-by-step discussed in detail. The goal with the validation with AM experts was to identify faulty steps in the process. With the Capgemini consultants the goals was to test the understanding of the concepts used to evaluate the tool. Furthermore, the validation sessions identified whether the user understands the terminology in the system.

5.2.3. Validation sessions

In order to formally validate the developed tool from chapter 4, a number of hypotheses have been drawn up. This validation is aimed to identify to which degree consultants are able to efficiently assess possible AM applications to identify appropriate business cases.
Per level a number of hypothesis are drawn up, this should validate what specific functionalities are understood by the consultants and which need extra attention. When the consultants of Capgemini can identify possible applications for AM the tool will be an added value to the services that the AIE at the moment delivers. The methodology is suitable for Capgemini when 3 out of the 4 participants are able to guide the process to a desirable end result. Expected is that participants with little to none technical experience have troubles using this methodology. Some aspects in level two and three are quite technical, this could be a bottleneck for the end result.

Prototype

After the evaluation sessions the prototype has been improved and some inconsistencies were clarified. The improved version is structured in the same way but the overall process has been made more transparent. Even so, tips and suggestions are added to explain some terminology because, in contrast to the evaluation session, the researcher cannot help the consultant. The prototype should allow the user to work with the method and enable them to ask relevant questions and obtain information in a structured way.
For the validation session one case study has been modelled statically in the system. This makes the transitions clear between the levels and the limited functionalities less vulnerable for inaccurate use. A list of parts has been integrated and some are pre-selected to mimic the process. For example in the part selection of the second level, only three parts that have to be selected remains when the filter criteria are applied. Everything from the third to the fifth level is modelled statically except for the decisions, this still require human judgement. And specifically these judgements have to be validated. The tool should guide the process efficiently but do but it does not impose decisions.

Differences with the prototype described in chapter 4
The largest differences with the prototype is with level 2, from the primary business focus matrix the users were guided to define the depth of study by themselves without many indications. The primary business focus had to be selected on the basis of some benefits than could be obtained but these could not be related to one specific field of the matrix, so participants had troubles selecting just one field. Level 2 included a justification of the selected direction in the form of challenges, this prove to be counter intuitive because this should be part of the decision for the business focus. Furthermore, the part selection interface has been adjusted because the weighting factors used to rank the parts in level 2 could not be defined objectively. Also the method of entering parts into the system was done manually and the best part is selected relative to all provided parts, which can cause an inappropriate analysis of the wrong parts.

Validation procedure

To validate the objectives the form of a role play is chosen as a method to find out in which degree consultants are able to efficiently assess the appropriateness of AM. The interviewee plays the role of consultant and has the task to identify the appropriateness of using AM in the organisation of the visiting client, in this validation known as the researcher.
The researcher acts like the company by asking fictitious questions. The company wants to investigate the possibility of using AM to improve their current processes. With a list of fictitious parts and goals the consultants have to ask questions to the researcher to find out how this objective can be realised.

Per level, a scenario have been developed which the consultant have to be used in order to stimulate the use of all aspects of the methodology. During the roleplay the organisations (researcher) asks questions that the consultant have to respond. When a consultant just clicks through the method and lacks to ask questions then clarification have to be given.

The scenario story
The organisation is a supplier of car interior products. They produce many different parts for various car brands. They deliver special editions often and offer aftermarket services to customers, both often in small quantities. Because of the low demand responsiveness and sporadic demand they cannot serve their customers well. Due to the media attention the organisation wants to know to which extend AM is suitable for making their business processes more efficiently. Ultimately, they want to investigate is it is possible to use AM for the production of spare parts. The organisation has provided the consultant with a list of parts of which 3 parts, shown in figure 4.7, have to be elaborated in more detail. The consultant have to recommend one of the three parts to use in the rest of the process. Finally, the selected part can be produced with AM but it is currently not economically wise.

Hypotheses
Per level several hypothesis are drawn up that test the ability of the consultants to identify the appropriateness of AM with the tool. In this way the methodology is validated whether it is able to support the process and information gathering. For each hypothesis expectations of the outcomes are described on beforehand.

	Hypothesis	Expected outcome
Level 1		
1.	The consultant asks questions about the current level of knowledge of the organisa-tion	The consultants asks this question in the first level, they build upon what they already know
2.	The consultants is able to explain AM with the tool? Relevant to the organisation.	With the help of the first level the con-sultant is able to explain the character-istics of AM, layer by layer, 3D model, possible materials, different types and terminology.
3.	The consultant asks the reasons for adopt-ing AM why would that be an added value? The goal, why to use AM?	These type of questions is asked while they try to identify a possible business driver.
4.	The consultant asks questions about the challenges (that apply to) the organisation (and are used to select the primary busi-ness focus)	A direct answer cannot be given on the adoption reasons, therefore the con-sultant needs to asks the questions about the challenges of the organisa-tion
5.	The consultant is able to select the right business driver with the help of the matrix	Based on the provided information the user selects the improve process flexi-bility
Level 2		
6.	The consultant asks questions about the depth of study and is able to identify the depth of study	The consultants asked questions about the type of applications they aim to use and what where in the lifecycle they want to apply AM
7.	The consultant is able to identify the right products	The consultant raises questions about the reasons and goals while they try to identify a possible business driver.
8.	The consultant is able to explain the reason-ing of part selection	The consultant explains what type of filters are applied and why these filter criteria are important for the selection
9.	The consultant is able to select potential parts and is able to pinpoint the possible benefits	The consultant with the help of the provided additional data able to assign complexity factors and AM specific ad-vantages to the parts.
Level 3		
10.	The consultant asks questions about the (available) requirements as addition to the selected part	The consultant asks about the re-quirements of the selected part and enter them into the system (i.e. sur-face roughness, accuracy, material)
11.	The consultant is able to explain the reason-ing/ranking of the most suitable production methods	The consultant explains the best meth-od based on the shown criteria, ability to meet requirement, costs and similar-ity.
12.	The consultant advises and selects the most potential production method including post processing methods	The consultant advises to proceed the assessment with the SLM process be-cause it can reach almost all require-ments.

	Hypothesis	Expected outcome
Level 4		
13.	The consultant mention the calculated major cost drivers of the initial calculation	The consultant mention each cost driv-er and the impact on the total costs
14.	The consultant can explain the impact of future developments on the future appropriateness (economic considerations)	The consultant can explain the impact of possible future economic considera-tion like build speed, machine costs, machine utilisation, material price, post processing on the cost drivers.
Level 5		
15.	The consultant is able to mention the technical consequences and impacts and possible barriers of the decisions made.	The consultant mention the technical consequences of the final selected part
16.	The consultant can explain the follow up steps, design guidelines and points of attention	The consultant mentions the follow up steps that can be taken to further de-velop the part
17.	The consultant evaluates if the goals, set in the first level, can be met	The consultants evaluate the goals set at the beginning of the assessment
18.	The consultant can advise possible interesting parties that can help them to bring their solutions to life.	The consultant identifies and advises external parties or suppliers.
General hypothesis		
19.	Is the Capgemini expert able to identify appropriate applications suited for AM?	The consultant is able to identify the appropriate part best suited for AM.

Table 5.1. Hypothesis for the validation sessions

Participants

For the validation research a couple of Capgemini consultants are asked to participate in a validation session. In the end, four consultants were willing to help me validate the methodology. Participant 1 has a FDM printer and at home but does not have a technical background. Participant 2 has an engineering degree in industrial design but does not have experience in the field of AM. Participant 3 is technically oriented consultant and has lot of interest in AM but has no degree in engineering. The last consultant, participant 4 is a consultant in the field of energy and utilities and no technical background in the field of manufacturing.
This difference in background knowledge can be used to obtain insight to which degree engineering knowledge is required to use this methodology with DSS effectively.

5.3. Results and analysis

Finally, both the evaluation session and validation sessions are conducted and data is recorded. The results of the evaluation session are more subjective as a result of the chosen method. In contrast, the hypothesis in the validation sessions can be identified more objectively. Lastly, the methodology is compared with the existing methods and the results are discussed.

5.3.1. Evaluation interviews

Based on the validation process described in section 5.2.2, per level and functionality the comments are collected and presented to obtain insight in the bottlenecks of the methodology. Special attention is paid to the understanding, simplicity and efficiency of assessment and evaluates if the user has all the required knowledge at the right time. Feedback from the usability evaluations are collected per level and the most important result are shown below. The complete reports of the evaluation results and of the interviews can be found in appendix 8.6.2

Level 1

- All participants indicated that informing is an important functionality to create a common understanding, integration of case studies and other examples could be useful.
- The AM experts noted that the images and graphs used (economies of scale and economies of scope diagrams) are generalized, when these are interpreted incorrectly this can lead to problematic statements,
- The use of abbreviations and terminology was unclear and inconsistent,
- Starting the process by selecting a goal was helpful, however multiple participants mentioned a possible overlap between the fields and wanted to select multiple goals

Level 2

- Determining the depth of study has been well received, but the question that aimed to identify the scope were too direct and could not be answered directly,
- For the part selection the interviewees could easily model the quantitative criteria of the part, but the most had troubles with specifying the complexity of the part. Especially the interviewees with little to no engineering background had troubles identifying the complexity criteria. More explanation of each complexity parameters was mentioned as helpful.
- The method for ranking the selected parts was unreliable and not transparent. The weighting factors used could not be defined objectively and the ranking was relative and there was a possibility that a bad part could be selected.

Level 3

- Modelling the requirements was logical and could be performed by non-expert users.
- It is mentioned by expert users that more requirements can influence the part selection, however this makes requirements gathering even more complex for non-experts,
- Some interviewees wanted to validate the outcome of the process selection algorithm with an AM expert, this noted that transparency is important in these stages,
- Level 4
- Providing a future perspective is interesting for clients but interviewees were hesitant to use the results of the preliminary cost calculations, because they wanted to know what the reasoning was behind these future prediction
- The calculations for economic scenarios were perceived as a black box. Building future scenarios on the basis of data is more useful, this gives more guidance and confidence in the results.

Level 5

- At the end the feedback loop was not closed, interviewees requested feedback how the part helps to achieve the selected primary business focus,

- Besides advising possible technological partners, advising what type of skills and competences are required when they want to develop the business case in-house.

5.3.2. Validation sessions

During the role play described in section 5.2.3, the ability is determined in what degree consultants meet the hypothesis.
All data points are collected and inserted in table 5.2. There are three categories in which the hypothesis can be fulfilled; not (no), partially (par) and full (yes). Afterwards points are assigned to each category; no=0, par=0,5 and yes=1 these totals are calculated and shown in the last column.

Hypothesis	Participant 1	Participant 2	Participant 3	Participant 4	Total
Level of expertise in AM	+	-	-	-	1
Level of engineering expertise	-	+	-	-	1
Level 1					
The consultants asks this question in the first level, they build upon what they already know	yes	yes	yes	yes	4
With the help of the first level the consultant is able to explain the characteristics of AM, layer by layer, 3D model, possible materials, different types and terminology.	par	yes	yes	par	3
The consultant raises questions about the reasons and goals while they try to identify a possible business driver.	Yes	no	yes	no	2
The consultant needs to asks the questions about the challenges of the organisation	yes	yes	yes	par	4
Based on the provided information the user selects the improve pro-cess flexibility	yes	yes	yes	yes	4
Level 2					
The consultants asked questions about the type of applications they aim to use and what where in the lifecycle they want to apply AM	Yes	par	yes	yes	3.5
The consultant can explain what they intend to do and what type of filters they want to apply.	yes	yes	yes	yes	4
The consultant explains what type of filters are applied and why these filter criteria are important for the selection	par	no	par	no	1
The consultant with the help of the provided additional data able to assign complexity factors and AM specific advantages to the parts.	no	par	no	no	0.5
Level 3					
The consultant asks about the requirements of the selected part and enter them into the system (i.e. surface roughness, accuracy, mate-rial)	yes	yes	yes	yes	4

Hypothesis	Participant 1	Participant 2	Participant 3	Participant 4	Total
The consultant explains the best method based on the shown crite-ria, ability to meet requirement, costs and similarity.	yes	par	par	no	2
The consultant advises to proceed the assessment with the SLM pro-cess because it can reach almost all requirements.	no	yes	yes	no	2
Level 4					
The consultant mention each cost driver and the impact on the total costs	no	no	no	no	0
The consultant can explain the impact of possible future economic consideration like build speed, machine costs, machine utilisation, material price, post processing on the cost drivers.	no	par	par	no	1
Level 5					
The consultant mention the technical consequences of the final se-lected part	yes	yes	yes	yes	4
The consultant mentions the follow up steps that can be taken to further develop the part	no	no	yes	yes	2
The consultants evaluate the goals set at the beginning of the as-sessment	no	no	no	no	0
The consultant identifies and advises external parties or suppliers.	yes	no	yes	no	2
General hypothesis					
The consultant is able to identify the appropriate part best suited for AM.	no	par	par	no	1

Table 5.2. Results of validation sessions

Participants indicated that it was not a problem to practice a couple of times to learn how the tool works and can be used efficiently. In some cases the interface elements were confusing, however these did not affected the working principles because the participants were able to explain what they intended to do.

During the sessions when there was no information available, participants started to make thing up, some of them were right but sometimes they were incorrect. At that point the methodology did not satisfy the users knowledge needs. These situations has to be prevented at all times, when both the consultant and a representative of the organisation are not expert users it should not be possible for them to result with strange recommendations. Right now the user is able to make mistakes and assess parts more positively than they are in reality. When the user forgets to model a requirement in the third level can have a major impact on the final process selection.

Overall, 3 out of 4 participants noted that they missed the big picture and they faithfully followed the process but had no clear view of the whole process. As can be seen from the total number in the right column the first level and the beginning of level 2 can be performed by people with little to none AM expertise. A prerequisite is a basic understanding of engineering principle in general to go into greater technical depth. Some participants thought this methodology dove too deep in the engineering part of the assessment. When in level two the participants have to assign complexity factors to parts the provided explanations did not help. Also, questions were raised to which extend it is interesting to know what material and technologies are being used for clients with a business background.

As can been seen in table 5.2 every technical functionality of the tools is hard to use for people with little engineering knowledge. Besides they do not see the relevance of using a technical perspective on the assessment, they often insert faulty information based of wrong assumptions. This lack of technical expertise can be a problem when this tool is used in a real situation. Furthermore, the major bottle neck is the fourth level, besides that it is not fully developed the working principles provide not enough guidance to trust the outcomes. It is designed to offer insights in the cost drivers but none of the participants was able to explain something useful from this data. Just like with the evaluations sessions they were not able to obtain the shown information and therefore it needs a full revision.

5.4. Conclusion

The goal of this chapter was to validate the developed methodology in both usability, understanding and effectiveness. Two different methods have been employed in two different stage of the development.

Evaluation sessions

The first used method was an evaluation of a preliminary developed prototype to identify early design flaws and faulty thinking tracks. In these evaluations the researchers aimed to test the usability and asks the opinion about the process and used methods.

Besides a few remarks, the first level is well received. The terminology can be used more consistent and a business focus was not easy to select because there were no clear guidelines or situation descriptions when to use which goal. The part selection in the second level requires attention. Two major assumptions prove to be wrong, first the ranking of the parts was based on weighting factors that could not be thoroughly defined. Second the ranking relative, this caused that even one part is the least bad could be selected and this could result is a faulty assessment result. Modelling requirements in the third level is simple with easy requirements but when it becomes more complex engineering knowledge is required. The economic considerations in the fourth level are perceived as a black box because the how the values are calculated could not be traced back easily. Therefore the methodology must be more transparent and consistent in use. Results of the evaluation sessions have been used to improve the prototype for the final validation. The process stayed the same but the implementation has been changed in some levels.

Validation sessions

In the last session the assessment methodology has been validated more thoroughly. In a role play is chosen as a mean to test the hypothesis. During the validation session the prototype was built for one specific case and therefore better able to mimic a real scenario. Although still some functionalities are missing and are displayed statically the participants were able to use the methodology correctly.

With the validations is shown that the parts in the assessment that require engineering knowledge performed poorly compared to the first two levels where no engineering knowledge is required. When user started to make things up this was harmful for the process and result if there are no experts present. This could result in misguided recommendations at the end. The lack of technical expertise can be a problem when this tool is used in a real situation. In these situations the participants did not ask the right questions and lack to provide relevant information.

Ultimately, the participants were not fully able to efficiently assess the situation. Because the prototype was statically and when the participants made a mistake, they were corrected and brought back on track. Also the method did not include to build a full business case. Many more aspects are needed for to define a viable business case.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Introduction

This final chapter of this thesis concludes the research by answering the research questions. In this chapter the findings are consolidated in conclusions and also describes the limitations of the study. The limitations of the research are pointed out and the recommendations for future improvements are presented. This section describes the recommendations for the methodology itself and for further research.

6.2. Conclusions

Clients want to have insight in the application for AM on a high level how it can be applied in the organisation. The existing methodologies to identify the possible applications are not suitable for Capgemini because it requires highly in-depth knowledge or are too shallow. Therefore a DSS is developed which supports the consultants and clients to identify the appropriateness of AM in an organisation. The objectives of the development was to enable Capgemini consultants to find appropriate applications for AM. With the help of a DSS the consultant should be able to ask relevant questions to identify the parts that matters the most to the clients. The assessment methodology consists of multiple level which enable a staged identification and has multiple goals in each stage. Consultants can use the developed tool as guidance during the session to create awareness and the whole identification process. With such activities Capgemini can advise organisations in an early stage to provide a clear overview of the available possibilities. The methodology is validated with based on two types of research first the method is evaluated for understand ability and user friendliness and, secondly lastly the working principles are validated with potential users.
The objective described in the first chapter of this thesis is only partly fulfilled. The objective was aimed to develop an assessment methodology which is supported by a DSS that contains and presents relevant knowledge in each stage of the decision making process in order to determine the applicability of AM. The validation session showed that users lack engineering knowledge and therefore were unable to identify the right product and/or process

Limitations of the study

This study aimed to identify appropriate business cases for organisations, has a number of limitations and has resulted in many other possible research directions. The first limitation is the scope of the project. Developing a full assessment methodology was not possible in the available time. Several times during the process the scope has been narrowed down but it remained an extensive task. Therefore only the process structure and the used tools are validated.
The method is validated with four people, more would have been beneficial to the identification of possible bottlenecks. Also performing some pilot studies would have provided different insights, when this process had been validated together with clients the perceived value could be identified. But this approach requires a better developed DSS and training of Capgemini consultants without AM knowledge.

6.2.1. Research questions

The main research question is divided into serval sub questions and this section aims to conclude the answers on these questions.

SUB RQ1: What knowledge is required to realise a common understanding among decision makers in order to assess the use of AM efficiently?

In order to create a common understanding of AM, the decision maker should must be aware of the following aspects: basic principles, available technologies and materials together with the advantages and benefits that might result from using AM. Furthermore, a common understanding could be realised by comparing AM with the well-known traditional manufacturing methods. In this way decision makers can obtain an understanding of the differences a special characteristics of a layer-by-layer process. When all this information is combined and structured logically it is possible to manage the expectations and know to what extend AM is applicable to the organisation. The decision maker should have an understanding of the benefits and limitations of the technology. Based on this data, organisations are able to have obtained the high level knowledge to start the AM assessment efficiently.

SUB RQ2: How to compare the capabilities of AM with other (traditional) manufacturing methods?

Although both technologies are fundamentally different in their basic principles it is possible to compare them. Directly comparing AM with traditional production methodologies require throughout understanding of the differences between the capabilities. Comparing the capabilities does not only require an evaluation of the technical side but also additional implications like the design approach have to be considered. AM has to be approached in with a different mindset than with traditional manufacturing. Making a process selection depend on three factors; design, material and processes. The technical aspects and the economic aspects have to be considered as well. Through the differentiation characteristics, the uniqueness of AM can be defined.

SUB RQ3: What knowledge should the DSS contain and how should this be structured to present relevant information for each stage in the decision process?

During this study it has been found that during the process the depth of knowledge can gradually be increased. Knowledge requires data, models, facts and rules together with context factors when they might be applied. Knowledge provides alternatives; when requirements or criteria are known decisions can be made. The knowledge base in the DSS contains descriptive, procedural and reasoning knowledge. Such base contains information about relationships between data and consists of rules that identifies or rejects alternative solutions. Structuring knowledge in semantic networks are an easy way to represent and understand knowledge.

SUB RQ4: To what extend are existing methods able to identify appropriate business cases for AM?

The comparison of the current methodologies resulted in an overview of the disadvantages of the possible methods. Web based tools were too shallow in order to define a business case from the resulting data. For the scientific assessment methodologies a specific business could not be determined. In contrast the consultancy companies and the have a clear goal to identify where value can be created with AM. These services have various ways how they approach the identification process. Considering the business the business case from one perspective is not sufficient. The methodology have to assess at least the technical and economic side of the business case. Considering possible barriers should be done to prevent implementation challenges, if the solution is technical and economical viable but is cannot be used or implemented in the industry, the case is not appropriate.

SUB RQ 5: How to identify appropriate business cases that use the benefits and capabilities of AM?

Business cases should highlight aspects like strategic fit, economic and commercial viability and possible managerial risks. During the assessment process the decision maker is able to consider multiple alternatives that can have impact on the appropriateness of the business case. Appropriate business cases for AM can be identified when one or more of the process capabilities offer possibilities to differentiate itself from traditional manufacturing. In order to create competitive advantage one has to consider the competitive priorities; quality, flexibility, costs and time. Through part selection organisation can identify parts that might hold great potential to benefit from the capabilities. Designers and engineers have to be aware of these specific capabilities and benefits where parts can benefit from.

SUB RQ6: How to assess the possible impact of AM on the product in terms of technical performance economic considerations?

During the selection procedures for the part and the process, requirements have to be modelled. Based on the algorithm the best fitting production methodology can be identified. The algorithm suggests alternative production methodologies matching the requirements. However, not all requirements are equally important or are available. These unknown requirements creates white spots. These spots contain requirements that are automatically assigned by the production method. Capabilities determine the impact on technical performance of the product. For the impact of AM on the economic considerations organisations have to use different costing models like life cycle costs. In these models more aspects have to be evaluated that might result in a higher economic impact.

MAIN RQ: How can consultants with little AM knowledge efficiently assess possible AM applications for clients to determine appropriate business cases?

Therefore, the assessment methodology is formalised into an interactive DSS of which a prototype is been built in Excel. In order to structure these process efficiently there has been chosen for a multi-level methodology where at each level the degree of knowledge increases. The DSS can provide the mandatory information about AM and the interface enables decision makers to structure the gathering of internal information. Resulting, the match between the current position and the objectives of the organisation and the possibilities AM offers, create possible applications which are appropriate for the organisations. Valuing the alternatives in terms of technical and economic aspects concludes the appropriateness of business cases.

6.3. Recommendations

The main objective of this research was to develop an assessment methodology that is assisted by a knowledge based decision support system which can be used by consultants with little AM experience to identify the appropriateness of using AM in an organisations. While this objective has been partially achieved, future work should be focused on further fulfilling this objective. In order to improve the methodology recommendations are proposed. Most recommendations are identified during the user testing. Some of the functionalities were considered as not transparent, unclear and unintuitive by some participants.

Determining economic considerations
Level 4 is still a point of attention. The aim was to provide insight in the cost considerations and cost drivers of the selected part but during the validation sessions the participants were not able to grasp the meaning. However user requested about other economic functions like investment costs, Return on Investments and opportunity costs. As¬sessing the total impact of the business case around AM could prove difficult without having not all information.

Clear holistic overview of the process
The process has to be made clearer in order to assist the participant to relate every action to the goal. This has to be visible for the user for any decision they make. When such functionality is interactive user can see the effect and impact of the decision much faster.
Perform pilot studies
Unfortunately, the assessment methodology has only be validated within a fictional environment. It is very valuable when the same process is validated with multiple actual business issues. In this way the real added value can be researched.

Develop list with potential partners
In order to close the feedback loop in the fifth level Capgemini should start by keeping track what partners are valuable in which situations. This require acquisition of new partners in the field of AM. Advising organisations in the last level increases the value Capgemini can offer to the assessment process. Identifying the right partners is crucial for a well-planned implementation.

Expectations of Capgemini
Currently there is a large contradiction; Capgemini has a need for AM knowledge but do not want to act like an expert in this field. In the end integrating AM into the future business offering will require technical expertise. Starting in the field of AM requires more effort in knowledge gaining activities. More activities have to be held to stimulate the publicity of AM at Capgemini. The willingness to give professional advice in the field of AM requires attracting new people with an engineering background. Although these services can be outsourced in the beginning it is important to obtain knowledge and experience in the field. This developed methodology can be used as a starting point for the further development of the service offering in the field of AM. Capgemini could play a role as initiator and network partner to develop a network with other organisations each with their own expertise and network.

Expert users
It is crucial during the use of the methodology that non expert user are not able to provide faulty recommendations. At the moment the methodology can be misused very easily, at each stage were the consultant has to enter or assign technical data this increases the likelihood of providing a invaluable recommendation.

In next version it would be nice when the methodology includes the product development, supply chain and organisational factors to identify the most appropriate factors. At the moment only technical high level considerations are used for the identification.
In a future version, the methodology could have many more features, during the validation and evaluation session multiple suggestions are mentioned to bring the tool to the next level.

General

1. Develop a web-based interactive DSS which is simpler and more user friendly to further validate the working principles of the methodology with such system,
2. Connecting and maintaining the databases which are online available to the system to ensure an up-to-date system. Linking these modules and libraries to the system have to be checked for inconsistencies and contradictory facts. Some of the information will keep itself up-to-date since it is linked to public websites. But the rest of the DSS could be updated internally by one internal employee which is responsible for the updates,
3. Codifying expert knowledge with multiple experts to build a reliable system. They have to model the relations between the data in specific contexts,
4. This work has only addressed the initial stages before the initial concept definition stages in the project. A case study has to be developed to evaluate the whole process, starting with this methodology to the final utilization of the component,
5. The developed DSS have to be more self-explaining but anyway training is required to teach consultants how to use this tool efficiently. Now at the end always consultation of AM experts is required to evaluate the outcome, User of the system wanted to validate the outcome of this level with an AM expert because they did not trusted the algorithm and they were not able to recreate the reasoning.
6. Overall, the methodology has to be made more transparent, participants in the tests indicated that reasoning and explanation was just as important as the proposed alternative.
7. Construction of the economic future scenarios have to be based on datasets from experts, this gives guidance and more confidence in the outcome.
8. Closing the assessment with a feedback loop over the whole process, has to be developed. This includes an analysis of the ultimate impact of the part on the selected business driver for adopting AM.

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8. APPENDICES

8.1. AM Technologies

8.1.1. Binder jetting

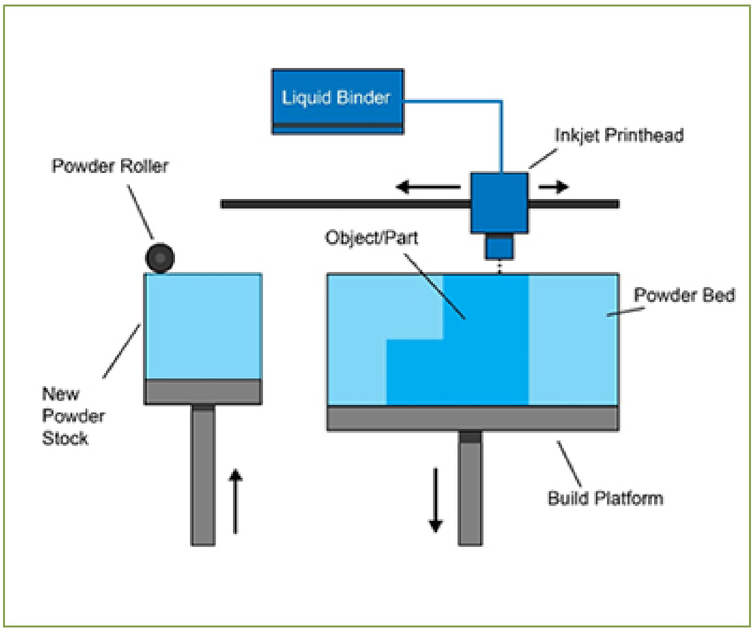

Figure 8.1. Binder jetting

Synonyms and abbreviations
3D printing, BJ

Process description
A binder jetting machine will distribute a layer of powder onto a build platform. A liquid bonding agent is applied through inkjet print heads bonding the particles together. The build platform will be lowered and the next layer of powder will be laid out on top. By repeating the process of laying out powder and bonding, the parts are built up in the powder bed.
Binder jetting does not require any support structures. The built parts lie in the bed of not bonded powder. The entire build volume can therefore be filled with several parts, including stacking and pyramiding of parts. These are then all produced together. Binder Jetting works with almost any material that is available in powder form.

Advantages:
- Parts can be made with a range of different colours
- Uses a range of materials: metal, polymers and ceramics
- The process is generally faster than others
- The two material method allows for a large number of different binder-powder combinations and various mechanical properties

Disadvantages:
- Not always suitable for structural parts, due to the use of binder material
- Additional post processing can add significant time to the overall process

Materials

- Metals: Stainless steel
- Polymers: ABS, PA, PC
- Ceramics: gypsum
- All three types of materials can be used with the binder jetting process.

8.1.2. Material extrusion

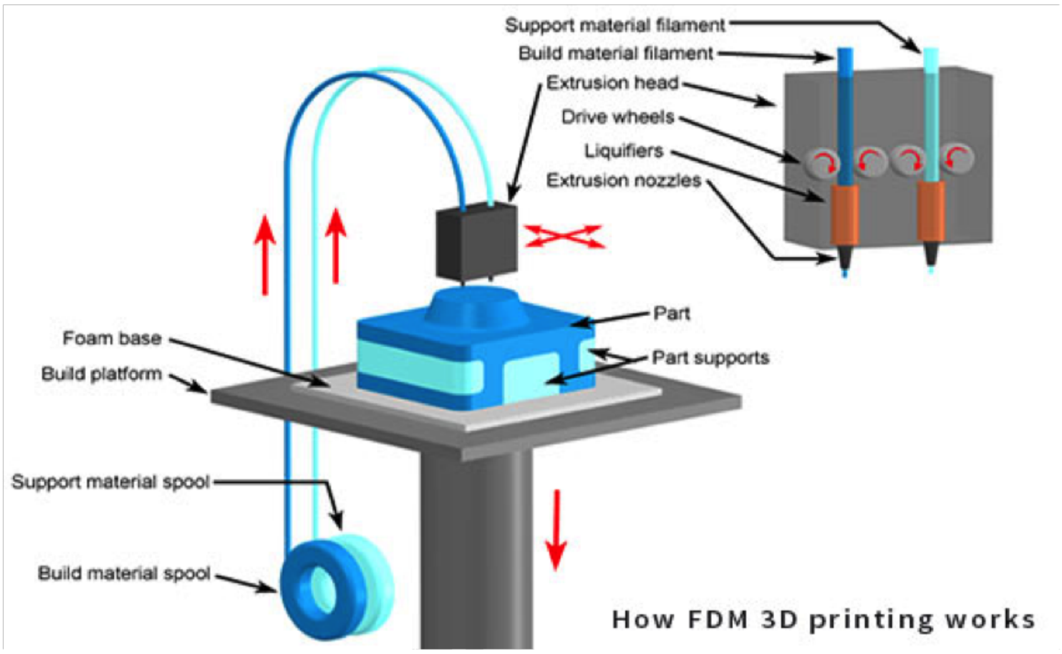

Figure 8.2. Material extrusion

Synonyms and abbreviations

Fused Deposition Modelling (FDM), Fused Filament Fabrication (FFF), Fused Layer Modelling/Manufacturing (FLM).

Process description

A fused deposition modelling machine melts a plastic filament and extrudes it through a nozzle. The melted material is laid down on the build platform, where it cools and solidifies. By laying down layer on layer the part is built.

Fused deposition modelling requires support structures which anchors the parts on the build platform and supports overhanging structures. Through the use of a second nozzle, the support structure can be built in a different material. Several parts can be produced at the same time as long as they are all anchored on the platform.

Advantages:

- Widespread and inexpensive process
- ABS plastic can be used, which has good structural properties and is easily accessible
- Disadvantages:
- The nozzle radius limits and reduces the final quality
- Accuracy and speed are low when compared to other processes and accuracy of the final model is limited to material nozzle thickness
- Constant pressure of material is required in order to increase quality of finish

Materials
The Material Extrusion process uses polymers and other plastics.
Polymers: ABS, Nylon, PC, PC.

8.1.3. Sheet lamination

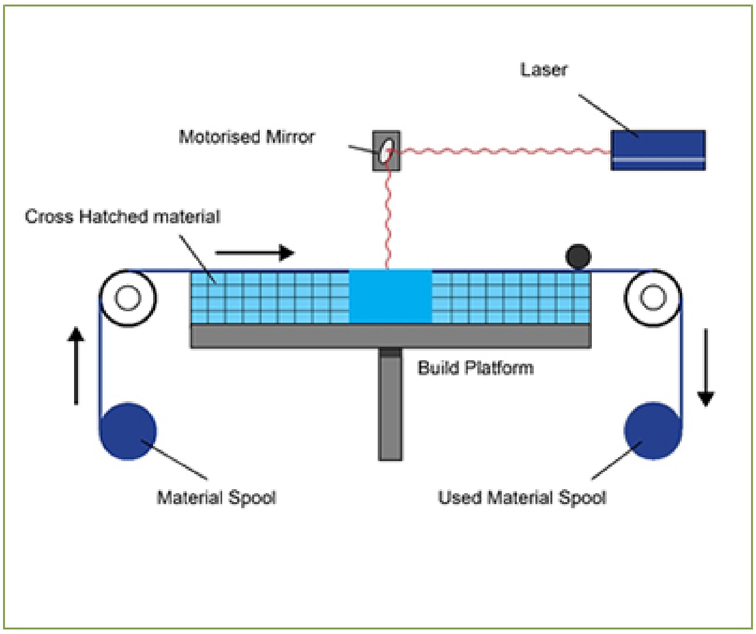

Figure 8.3. Sheet lamination

Synonyms and abbreviations
LOM, The Ultrasonic Additive Manufacturing (UAM)

Process description
Laminating (LOM) is one of the first additive manufacturing techniques created and uses a variety of sheet material, namely paper. Benefits include the use of A4 paper, which is readily available and inexpensive, as well as a relatively simple and inexpensive setup, when compared to others.
The Ultrasonic Additive Manufacturing (UAM) process uses sheets of metal, which are bound together using ultrasonic welding. The process does require additional CNC machining of the unbound metal. The process is low temperature and allows for internal geometries to be created.
Post processing requires the extraction of the part from the surrounding sheet material. With LOM, cross hatching is used to make this process easier, but as paper is used, the process does not require any specialist tools and is time efficient. Whilst the structural quality of parts is limited, adding adhesive, paint and sanding can improve the appearance, as well as further machining.

Advantages:
- Benefits include speed, low cost, ease of material handling, but the strength and integrity of models is reliant on the adhesive used (Krar and Gill, 203)
- Cutting can be very fast due to the cutting route only being that of the shape outline, not the entire cross sectional area

Disadvantages:

- Finishes can vary depending on paper or plastic material but may require post processing to achieve desired effect
- Limited material use
- Fusion processes require more research to further advance the process into a more mainstream positioning

Materials
Effectively any sheet material capable of being rolled. Paper, plastic and some sheet metals. The most commonly used material is A4 paper.

8.1.4. Directed energy deposition

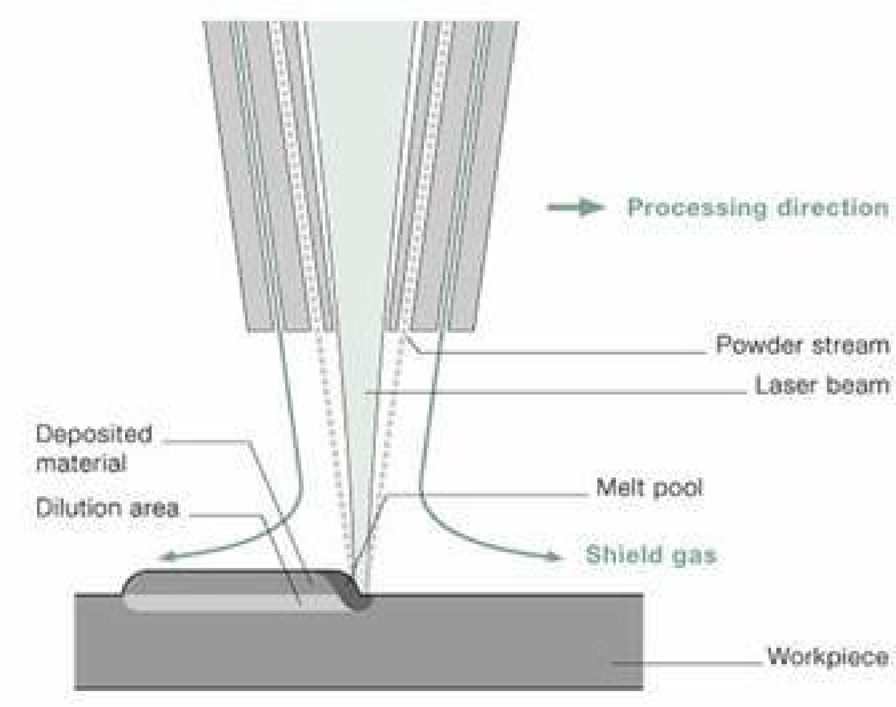

Figure 8.4. Directed energy deposition

Synonyms and abbreviations
DED

Process description
Focused thermal energy, such as a laser, is used to fuse materials by melting as the materials are being deposited to form an object. A typical DED machine consists of a nozzle mounted on a multi axis arm, which deposits melted material onto the specified surface, where it solidifies. The process is similar in principle to material extrusion, but the nozzle can move in multiple directions and is not fixed to a specific axis. The material, which can be deposited from any angle due to 4 and 5 axis machines, is melted upon deposition with a laser or electron beam. The process can be used with polymers, ceramics but is typically used with metals, in the form of either powder or wire.

Advantages:
- Ability to control the grain structure to a high degree, which lends the process to repair work of high quality, functional parts

- A balance is needed between surface quality and speed, although with repair applications, speed can often be sacrificed for a high accuracy and a pre- determined microstructure (Gibson et al., 2010)

Disadvantages:

- Finishes can vary depending on paper or plastic material but may require post processing to achieve desired effect
- Limited material use
- Fusion processes require more research to further advance the process into a more mainstream positioning

Materials

Titanium, Nickel and Copper, Stainless Steels, Aluminum and other special metals

8.1.5. Powder bed fusion

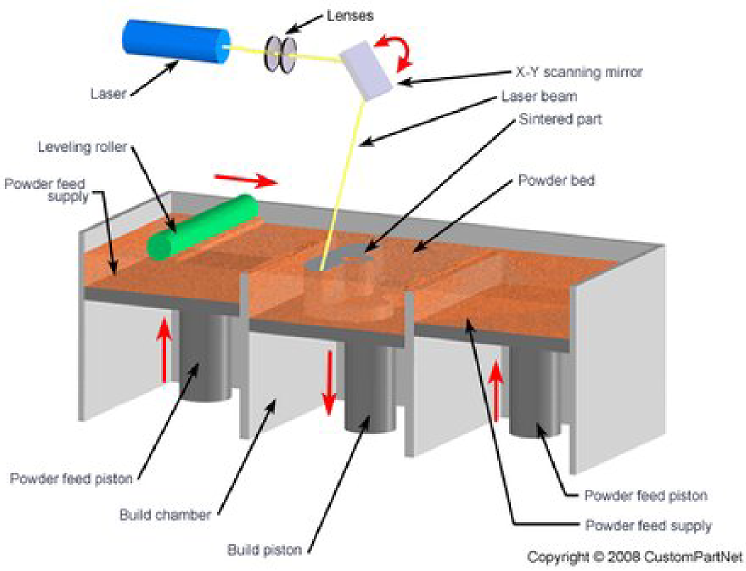

Figure 8.5. Powder bed fusion

Synonyms and abbreviations

The Powder Bed Fusion process includes the following commonly used printing techniques: Direct metal laser sintering (DMLS), Electron beam melting (EBM), Selective heat sintering (SHS), Selective laser melting (SLM) and Selective laser sintering (SLS).

Process description

Powder bed fusion methods use either a laser or electron beam to melt and fuse material powder together. The build platform will then be lowered and the next layer of plastic powder will be laid out on top. By repeating the process of laying out powder and melting where needed, the parts are built up in the powder bed.

Laser Sintering does not require any support structures. The built parts are sustained by the loose plastic powder. The entire build volume can therefore be filled with several parts including stacking and pyramiding of parts, which are then all produced together. The process chamber is preheated and under a protective gas environment.

Advantages:
- Suitable for visual models and prototypes
- (SHS) Ability to integrate technology into small scale, office sized machine
- Powder acts as an integrated support structure
- Large range of material options

Disadvantages:
- Relatively slow speed (SHS)
- Lack of structural properties in materials
- Size limitations
- High power usage
- Finish is dependent on powder grain size

Materials
The Powder bed fusion process uses any powder based materials, but common metals and polymers used are:
SLS and SLM: Stainless Steel, Titanium, Aluminium, Cobalt Chrome, Steel
EBM: titanium, Cobalt Chrome, ss, al and copper (Materials Arcam, 2014).

8.1.6. Material jetting

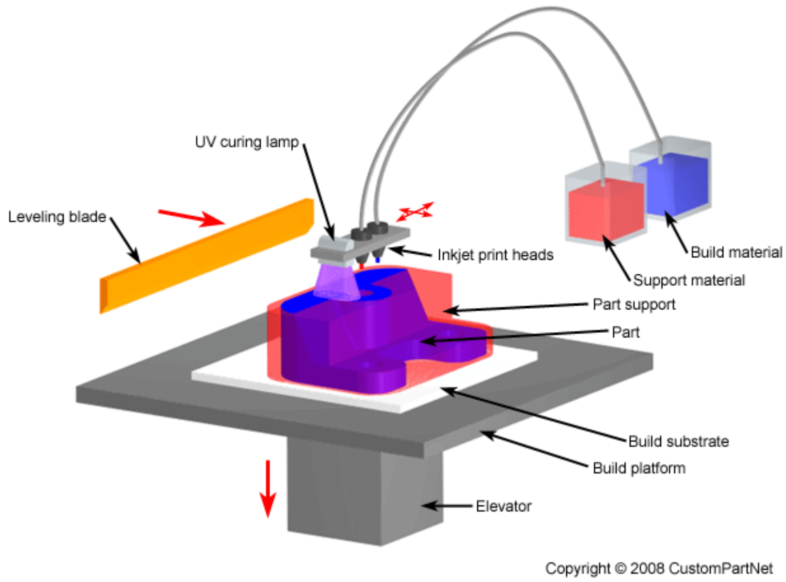

Figure 8.6. Material jetting

Synonyms and abbreviations
Multijet modeling, DOD, drop on demand, Thermojet, Inkjet printing

Process description
Material is jetted onto the build surface or platform, where it solidifies and the model is built layer by layer. Material is deposited from a nozzle which moves horizontally across the build platform. Machines vary in complexity and in their methods of controlling the deposition of material. The material layers are then cured or hardened using ultraviolet (UV) light.

Advantages:

- The process benefits from a high accuracy of deposition of droplets and therefore low waste
- The process allows for multiple material parts and colours under one process

Disadvantages:

- Support material is often required
- A high accuracy can be achieved but materials are limited and only polymers and waxes can be used

Materials

The material jetting process uses polymers and plastics.
Polymers: Polypropylene, HDPE, PS, PMMA, PC, ABS, HIPS, EDP

8.1.7. Vat Photopolymerisation

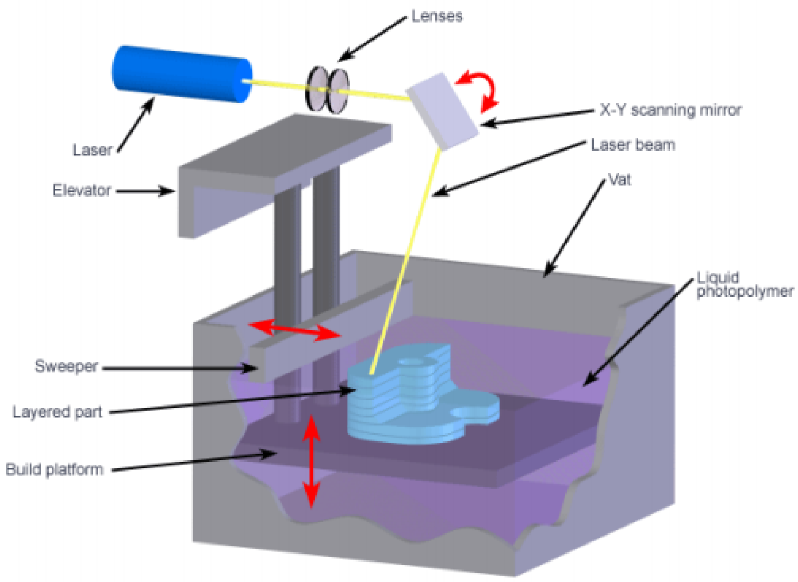

Figure 8.7. Vat Photopolymerisation

Synonyms and abbreviations

SL, SLA

Process description

Stereolithography machines build parts out of liquid photopolymer through polymerization activated by a UV laser. Parts are built on to a build platform inside a vat filled with the liquid photopolymer. The laser is scanning the surface of the vat which is solidifying. The build platform is lowered subsequently into the vat and the part is built layer by layer. Stereolithography requires support structures for overhangs, which are built in the same material.

Advantages:

- High level of accuracy and good finish
- Relatively quick process

Disadvantages:

- Relatively expensive
- Lengthy post processing time and removal from resin
- Limited material use of photo-resins
- Often requires support structures and post curing for parts to be strong

Materials

The Vat polymerisation process uses Plastics and Polymers.
Polymers: UV-curable Photopolymer resin
Resins: Visijet range (3D systems)

8.2. Cost models

In literature two costs models received the most attention namely Hopkinson & Dickens (2003) and Ruffo et al (2006). Hopkinson & Dickens (2003) calculated an average cost per part is calculated by dividing the labour, material and machine costs of all parts produced in one year. The authors made three crucial assumptions: 1) one part is produced on one machine for one year, 2) the machine utilisation ratio is 90% and 3) the build volume uses at a maximum effectiveness.
Ruffo et al. (2006) uses an activity based cost model, which means that each activity is related to costs. The authors divided the costs in direct and indirect costs; direct costs are the material costs and the indirect costs are based on the time of the activity multiplied by the cost rate. Production labour per machine hour, machine costs, production overhead and administrative overhead are the activities which are incorporated in the calculation of the indirect costs.

The assumptions which are made differs from Hopkinson and Dickens, Ruffo uses 1) a 57% machine utilisation, 2) and the costs of the part is calculated based on the total cost of the build. This assumes that all the products in the build envelope are the same, when different parts are combined Ruffo suggest using a method where costs per part is calculated proportionally to the size of the part.

8.3. DSS development methods

Turban DSS development in collaborations with the user. (Turban, 1995)

1. Step 1 – Select a problem to be solved
2. Step 2 – Select suitable software and hardware
3. Step 3 – Find suitable data sources
4. Step 4 – build or acquire relevant elements for the model subsystem
5. Step 5 – develop a user interface
6. Step 6 – Build the knowledge component
7. Step 7 – Put together all DSS components
8. Step 8 – Perform tests, evaluate results and improve the system
9. Step 9 – Train the users to use the DSS
10. Step 10 – Provide documentation and maintain the DSS
11. Step 11 – Modify the system to conform to the user demands.

Klein and Methlie developed a methodology to develop and implement a knowledge base DSS (Klein & Methlie, 1995).

Understand the users' goals these include recognition of the problem situation, an investigation of the problem, generating alternatives, identify decision criteria, evaluate suitable alternatives and ultimately select one alternative.
Define and understand problem boundary identifies the decision maker (end-user), the perspective of the decision maker in relation to the decision structure and decision boundaries.
Define and understand the decision process provides insight in the differences between users and their decision process.
Define a normative decision process for the problem requires analysis of the generic decision process.
Identify changes in the decision process When many users use the system, the process should be adapted.
Select a part of the system to support to define the starting environment of the user.
Functional analysis of the KB DSS has the purpose of defining the main functions and the system architecture of the KB DSS. For the knowledge base decision models, structured data and input forms are needed. The initial layout should demonstrate the use of data and models in the process.
Selection of a development environment is the decision to identify the most suited platform on which the system can be build. Klein and Methlie suggests some possibilities: standard programming languages, AI languages, Expert System shells, DSS development environments and KB DSS development environments. The choice depends on the required functions.
Implementation of the initial KB-DSS consists of steps including, data analysis and modelling, design of the decision model, modelling of the knowledge base and designing the user interface.

8.4. Business focus matrix

mary business ocus matrix	Competitive priorities			
	Quality Increased functionality, performance or quality	**Flexibility** Increased business flexibility and agility	**Time** Delivery improvement Time savings	**Cost** Improved financial Cost improvements
omer riences more revenue t orriented	Enhance product performance & functionality	Enable customer demand flexibility	Improve delivery speed	Reduce Total Cost of Ownership
rational llence e process efficiency	Improve pocess performance	Improve process flexibility	Reduce lead-time	Reduce process cost
business els for new models, new revenu stream	Develop new business performance capabilities	Enable new business flexibility	Enable rapid product introduction	Establish new cost structures

Figure 8.8. Business focus matrix

8.5. Challenges of business matrix

Goal: *Primary business focus matrix*	Competitive priorities: **Quality** Increased functionality, performance or quality	**Flexibility** Increased business flexibility and agility	**Time** Delivery improvement Time savings	**Cost** Improved financial Cost improvements
Customer experiences Create more revenue Product orriented	**Enhance product performance & functionality** Geometric complexity is high Production volume is low Lost improved performance occurs Low customer satisfaction rate High need for lightweight products Weight of parts is high but important Products are currently limited by the manufacturing method	**Enable customer demand flexibility** High importance of product variety Low ability/capability to offer product variety High amount of customised parts Low market responsiveness Large number of manual customised parts Large number of niche markets Sporadic product demand Low frequency of demand	**Improve delivery speed** Long time to market Long transport and distribution time Location of customers are highly spread Location of customers are far away Highly distributed customerbase	**Reduce Total Cost of Ownership** High lifecycle costs High costs total cost of ownership Downtime costs high Low volume high costs
Operational excellence Improve process efficiency	**Improve pocess performance** High amount of process steps Large number of changeovers Many assmbly steps, complex assembly Low impact (low output rate) of product development Process sustainability low Process effectiveness low High amount of material waste	**Improve process flexibility** Low demand responsiveness Problems with process planning Low effectiveness of production in small batch sizes Ease of changeovers in production is hard Sporadic product demand Low frequency of demand Unpredictable demand Reduce inventory by being able to better match supply to demand	**Reduce lead-time** Long Time to market Production lead time long Long setup times Slow speed of product development Influence of tooling on time to market high Process lead time long Slow product development High lead times due to opperations far from customer demand	**Reduce process cost** High tooling costs High production costs (due to complexity) Costs of opperation high Delivery costs high Material waste high Low volume high costs High costs due to tooling High costs involed with balancing end of stock Afterservice costs high
New business models Search for new models, create new revenu stream	**Develop new business performance capabilities** Gross margin on parts low (ability to offer premium products) Impact of product leaks high (Need for secured development) Large amount of product in the portfolio compete on price Troubles with adressing new product and/or new markets Design for X products	**Enable new business flexibility** Low customer involvement Not able to offer personalised products Ability to serve niche markets Ability to offer customised product is low High need fo supplychain simplification	**Enable rapid product introduction** Long Time to market Rate of new product introduction slow Slow speed to market High risks involved with new product introduction High need for supplychain simplification High product introduction risks, new business unsure	**Establish new cost structures** Establish new cost structures and revenu models High product introduction risks, financial risks high

Figure 8.9. Challenges of business focus matrix

8.6. Evaluation sessions

8.6.1. Protocol

Level 1

The participant is invited to navigate through the tool and together with the researcher each step is discussed. Starting at the first level some background information is provided give an overview of the occasion in which this level is used. Basically, this involves explaining the user that it starts by informing and creating awareness of possible uses of AM to organisations. When the user navigates through the tool there is paid attention to every important aspect to investigate if the can follow the procedure or understand the concepts and terminology used.

In the first level extra attention is paid to the advantage vs lifecycle diagram and the business driver matrix. The diagram is shown to the participant and their opinion is asked and how they interpret the goals of these diagrams. When they have trouble explaining the goal the researcher explains the intended use and clarifies potential ambiguities. If the user is on the right track the usefulness is discussed how this might be used to provide organisations with new insights. At the end of the first level a business driver is selected from the developed matrix. Expectations are discussed how these might influence the direction of the rest of the assessment methodology. Furthermore, it is investigated whether the participant is able to select the right box in the matrix. Then some dimensions of the matrix is discussed to eliminate certain ambiguities and examine is the participant think if there is some overlap is possible.

Level 2

In the second level two aspects are discussed into detail; first the possible barriers to adoption and secondly the selection of possible parts. In the prototype the screen with the barriers are displayed statically and in an abstract manner. The researcher explains that this level aims to place the organisation with both feet on the ground and mentions the possible barriers worth considering to prevent surprises at the end of the assessment. Questions which could be asked to identify the depth of study are reviewed whether they are relevant and fitting to be asked at this stage.

In the prototype, the part selection is made somewhat more interactive to give the participant an indication of the working principles. The researcher explains that not all parts can be printed and some are more suitable than others, and therefore part selection is chosen at this point in the assessment. Part selection should give users awareness for the aspects that make parts suitable for AM. Based on a provided scenario the user have to model this part into the system. On the basis of the ease with which the user the fills out the form, the understanding of the aspects are discussed holistically and individually.

Finally, the results of the part selection is discussed to examine whether the participants were able to understand the ranking of the parts.

Level 3

Proceeding through the third level, where the suitable production technologies are generated based on the part requirements. Underlying working principles are explained to the user and more detailed requirements have to be modelled by the user. Because the Excel tool is not able to perform the developed algorithm the results are presented statically to give an indication of a possible result.

The researcher asks if they are able to understand the concepts asked to gather the requirements, for example are they familiar with the terminology and are they able to define the surface roughness or the overall accuracy of the parts. This should make clear whether consultants are able to enter these requirements or do portfolio and production manager from the organisation have to be considered.

Level 4

In the fourth level the participants should obtain insight in the working principles of the economic considerations and the growth scenario creation. The researcher explains the working principles and that the outcomes are not exact values but are rather indicative. It is shown how the costs are calculated and on what databases these calculations are based. However, the user can use adjust the scenarios by themselves and are categorized in three scenarios; a most likely, most optimistic and a most pessimistic one. In order to determine the possible future economic scenarios, possibilities for incorporating another element that is able to provide short term and long term insights.

The participant have to respond and identify the real need for the functionalities in the level. Do they think it is really added value for the assessment to identify the appropriateness of AM.

Level 5

The last level is presented empty to the user to start a discussion about the content. The researcher describes that this level is intended to provide a summary of the whole procedure but the content has to be determined. Is it potentially interesting for Capgemini to include here some external partners that can help to take this business case to the next level? Or does it have to show different skills and competences required when considering to take this part to the engineering stage?

Closing and discussion

In the last stage of the validation session the researcher asks various questions to wherein the participant have to evaluate the whole methodology. These questions are shown below:

- What do you think of the whole process?
- Do you think the methodology is structured logically?
- Did you have all the required knowledge at the right time?
- Are there any aspects or functionalities in the methodology that included that are unnecessary?
- What parts of process were the most difficult to understand or use?
- Was there anything confusing about the levels?
- If yes, are there any changes you would suggest to make it less confusing?
- Does a user have a better awareness of the consequences and impacts of the decisions made?
- Can this methodology be used by Capgemini consultants (non-technical and non-AM experts)
- Is the collection of information is guided well and is sufficiently explained why some input is asked at each stage in the methodology?
- What could be a bottleneck for my solution?
- As a user do you have the feeling that you are better able to determine the appropriateness of AM?

8.6.2. Results

Level 1

All the participants agreed that informing the user with basic information has to be the first step before assessing the applicability. Especially, the Capgemini consultants indicated that this level is important to know the process capabilities and what factors are important before

the use of AM is even considered. The fact that the information is presented as Wikipedia-like structures is helpful. Some even suggested that it is better to present more information than needed but then the level loses focus. Capgemini consultants had the desire to be quickly up-to-date about what information specific to the situation.
The picture used to explain the basic principles gives a one-sided example of the additive technology. It is suggested that this image can be more generic at this stage or it should also show all working principles of the other technologies at this point. The abbreviations used to define various technologies are unknown to the consultants and have to be better explained. Subsequently, these abbreviations must be used more consistently throughout the assessment. The same applies to the use of the terms high volume and large batch size, in the prototype they mean the same but are used inconsistently.
The basic principles covered in the two graphs shows the differences between traditional methods and AM for the cost and complexity dimension. The graphs that indicate the quantity and complexity between AM and traditional manufacturing methods are good for introductory purposes. The problem with this AM graphs are that they make generalized statements and when these are not interpreted correctly they will lead to problematic statements.
The table which compares the traditional manufacturing technologies with all the different AM technologies is perceived generalized because there can be some exceptions that do not fit. It is good creating awareness but not for indicating the appropriateness of specific parts. The prototype contained a large table with all the different processes together with the technical and commercial names. Has to be interactive and searchable but does not have to be treated in detail, when an organisation has specific questions about the working mechanisms the can be found in this stage. Such overview is nice especially if it points out the specific industrial applications, it points down really fast to some technologies.

In the diagram of the advantages and disadvantages the opinions were mixed. Three of the four participants the intended use of the diagram was not clear and had to be explained in detail. Many information is in the diagram and that makes it hard to read and understand. It is suggested that this has be more interactive and in that way be more specific to the organisation. Then it might be helpful for organisation that do not have a clear idea of the advantages yet. Others mentioned to make it better readable the matrix can be made industry specific but it is hard to link some advantages to industries at this immature stage of AM. In this way it directly shows the essence of what is possible. Showing all the relevant advantages is valuable information to stimulate them to think about possible ways to realise them.
Giving a direction to the assessment was logical and it provided directly insight in the advantages that can result from AM. The competitive priorities can overlap and are highly related. It is hard to identify a specific box in the matrix. At this point a decision maker does not have an idea what the impact on the rest of the assessment is when they select a direction. Likewise the process could be more transparent, together with the motivation how the benefits are characterised in the matrix.
However, a couple of times it is mentioned if it is also possible to select multiple boxes. One reason could be because some objective are not one-sided, some objectives can consists of a multitude of factors. The other reason could be that interviewees indicated some overlap between the competitive factors, time can be expressed in costs. Two participants mentioned that these choices are about the whole picture and insight in all factors and not only focussing on one specific factor, the fact that you can become more efficient at one priority may be detrimental to the other factors and they have to be in balance.

Level 2

Putting organisation with both feet on the ground by presenting a list of industry specific barriers and consideration are indicated as helpful. Transparency is important how and why these barriers are relevant to the organisation. As a consultant you want this information as soon as possible in order to solve or circumvent the obstacles by taking counter measures.
Questions to determine the depth of the study have not been positively assessed. This type of formulating the question was too direct and it is the goal of the study to find out whether it is even appropriate to change the product or the process. At this point in the assessment the organisation are not aware of possible advantage their parts or process can benefit from. The question have to be formulated in a more positive way, but you do not want to stop the assessment at this point. An organisation who starts with evaluating AM will not be limited by the restrictions because these negative aspects are inherent to the maturity of the technology. Interviewees indicated that presenting such barriers is a welcome addition for consultants.

All participants are asked to model a part in the tool, this help to clarify the difficulties and identify ambiguities. It is found there is a difference in the modelling the current part or the expected part. The parts selection is intended to model existing parts to determine the suitability of each specific part. Inconsistencies in the part selection required to model the complexity of the current part with qualitative factor that do only apply to AM. The terminology used in these qualitative factors were hard to understand for non-expert users. Even the expert users were not able to identify the possible complexity factors that might apply to the part. An expert mentioned in order to define these factors an in-depth analysis of every part is required, but defining complexity in qualitative terms is a good approach compared to assigning a number in a range. As a consultant they are not able to identify these complexity parameters and this requires in-depth part knowledge form the client side. The participants indicated that they found it helpful when these factors are clarified with example pictures and additional data. It is noted that the questioned complexity aspects require a more in-depth knowledge, to solve this issues the part selection could work with specific advantages that can be applied. For example does the part benefit from a light weight structure, then lattice structures can be used. The advantages can help to determine the future complexity. The lead time was another bottleneck, when the current lead time is taking more than 30 days but for the prioritisation it is helpful to know the future required lead time.
Remarks were placed on the input method. Some participants did not know why the values have to be generalised in a range to enable reuse in the following levels. Other pointed out this input method is not suitable for large amounts of parts. Entering all parts by hand is a tedious task. Making a preselection of parts is necessary. Do organisation have to provide this data in order to complete the assessment or could the consultant perform these analysis before a session.
The methodology used for the ranking is considered questionable. Because the ranking is relative, there is a possibility that the best part from an unsuitable set of parts can be selected. Ensuring also absolute value removes this danger of misinterpreting the outcome. And secondly, with the ranking some parts are not assessed because they are not in the top, these part can also hold a potential for AM. The participants expected more transparency how these ranking are constructed and how the ranking relate to the selected business driver. In this stage multiple interviewees suggested additional reasoning that explains the ranking. AM experts indicated that defining good sets of weighting factors is hard to find such prioritisation parameters for each objective in the matrix.

Finally, participants did not understand why only one part is selected at this stage. Sometimes others can also be interesting for further analysis. Providing a more complete advice and justification have to include multiple parts. For the user it was not clear the ranking was an indication and not a hard decision, it provides a relative advice of the most potential part. Ultimately the ranking can be used for suggestions for further investigations.

Level 3

Modelling the requirements was logical and could be performed by Capgemini consultants. The third level is helpful especially when all the requirements have been supplemented with examples of indicator values. However in consultation with product or portfolio managers of the organisation it is possible to provide this information. Some of the factors had to be entered in the system for the part selection a reuse of this information is wishful to make it less tedious.

There are many more requirements and aspects which could be modelled that influence the production section. The fact that post processing is incorporated is valuable at this point and can provide direction to select the right technology.

In order to trust the outcome and present these suggestions to clients, two participants said they wanted to validate the outcome with an AM expert. Offering such recommendations for production technology require a system that has to be correct and always up-to-date this is indicated by participants as important. The AM-experts mentioned in order to maintain the database in this rapidly changing field is quite challenging.

Level 4

Providing insight in the possible future costs or cost drivers is relevant for organisation performing this assessment. Advising on the long term is hard with this part of the tool, for this additional data is required to make better reasoned predictions. For the perspective of a Capgemini consultant it is always interesting to give clients what the possible future expectations. This can give direction to the final decision whether the technology can be applied directly or in a couple of years. But these future insights is always good but have to be taken with a grain of salt.

Building future scenarios on the basis of data is more useful, this gives more guidance and confidence in the results. All participants had troubles with trusting this part of the assessment because it is perceived as a black box. Based on current future predictions it can be indicated in a certain time frame. But finding data with such predictions is difficult, no one will know have the technology will develop.

Level 5

At the end of the assessment the participants requested a feedback loop of the whole process and the selected business driver. The impact on the four competitive priorities is consider wishful to give an advice on all factors. When the organisation has insight in how this business case might fulfil the defined objective they can compare it to their current situation. Summarising the process is important in order to communicate the summarized process to other people or executives. The summary have to consist of the alternatives, decisions and criteria use in the part and process selection.

Besides closing the feedback loop the tool have to look forward and should suggest other technological partners that are able to take this business case to the next level. Advising what skills and competences an organisation needs is helpful when they want to develop the business case in-house.

Considering the technical consequences can be interesting when there is a high potential of fulfilling the objectives, in an early stage of the development this information is useful for engineers and designers. Offering this type of services is directly interesting to Capgemini, in this way they can be the middle man in the technical developments.

Overall indication

Capgemini consultants found it hard to understand at first. Using this tool should require a training because it consultants do not have to expertise on their own. Multiple participants note that this tool is not self-explaining at the moment. Especially the more technical orientated levels three and four require more in-depth insight in the AM field.

Overall, the participants think such tool might be helpful, but al lot of steps have to be made to make the tool more usable. Users of this tool have to be aware of the outcome of these analysis they have to critically discuss the results with an expert. The same counts for the economic considerations in its existing form, consultants indicated that they could not present the outcome with confidence because the system works with highly uncertain estimations.

However the process was logical, the steps are followed in the right way. The process is intuitive and the flow is right, like the starting point where the system informs the user is marked as an important feature of the assessment. On the question if the user has the right type and amount of knowledge at the right time in the assessment, remarks were placed on some explanation facilities.

The bottlenecks of the tool vary between the consultants and the AM experts, consultants think they are not possible to fill out the part selection form correctly because in-depth knowledge of the part is needed. The part selection is questioned, why the client has to make a ranking. Maybe there are similar parts that might be equally suitable and at the moment these are rejected. Providing a holistic picture of multiple parts might justify the investments for new AM machines sooner. When the typical product is generalised and modelled in the system the resulting advice might be applicable to more products. The more parts can be printed in a company the higher the suitability for the use of AM. One consultant wanted to know what the possible motive of the customer are to provide the (confidential) product data to Capgemini. With this tool clients have awareness after the part selection, how can these be convinced to provide this data. The tool cannot be used to analyse all the parts in the product portfolio of a company otherwise with this methodology it becomes a tedious task.

The user interface is not built for information reuse, for the part selection the values have to be generalised and in the process selection these values have to be entered again this can be made more efficient. And at the end of the process a functionality was missing was the feedback on the assessment and what it has contributed to the selected goal in the first level.