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Innovation Study for Laser Cutting of Complex Geometries with Paper Materials

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Abstract

Even though technology for laser cutting of paper materials has existed for over 30 years, it seems that results of applications of this technology and possibilities of laser cutting systems are not easily available. The aim of this study was to analyze the feasibility of the complex geometry laser cutting of paper materials and to analyze the innovation challenges and potential of current laser cutting technologies offer.

This research studied the potential and possible challenges in applying CO_2 laser cutting technology for cutting of paper materials in current supply chains trying to fulfil the changing needs of customer in respect of shape, fast response during rapid delivery cycle. The study is focused on examining and analyzing the different possibilities of laser cutting of paper material in application area of complex low volume geometry cutting. The goal of this case was to analyze the feasibility of the laser cutting from technical, quality and implementation points of view and to discuss availability of new business opportunities.

It was noticed that there are new business models still available within laser technology applications in complex geometry cutting. Application of laser technology, in business-to-consume markets, in synergy with Internet service platforms can widen the customer base and offer new value streams for technology and service companies. Because of this, existing markets and competition has to be identified, and appropriate new and innovative business model needs to be developed. And to be competitive in the markets, models like these need to include the earning logic and the stages from production to delivery as discussed in the paper.

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1. Introduction

Laser technology and material processing has been applied to paper and board cutting since 1970's. Still lasers main application in paper industry have been in slitting and scoring solutions (Powell et al. 1989, Powell 1993, Olsen 1988), even when it is well know that a CO2 laser is suitable for cutting other non-metallic materials such as glass, plastic, rubber, paper, wood, etc. In industrial environments, lasers are applied nowadays in many processes, including welding, hybrid welding, steel cutting, etc. (Ion 2005, Kah et al. 2010, Salminen 2010).

Most common general applications of laser processing are marking, cutting and welding. In addition to laser processing of metallic materials, also many industrial applications of laser processing of non-metallic materials, like polymer welding and cutting of wood-based materials, are widely used (Steen 2003, Caiazzoa et al. 2005, Eltawahni 2013). In addition to tougher and more robust materials, also really thin papers etc. can also be cut with lasers. In fact, it can be done with high cutting speed and with good cutting edge quality, but generally the main application of laser processing in paper material has been in marking, perforation, slitting and scoring type of applications. In this context, one of the first successful commercial industrial applications in area of laser processing of paper materials has been perforating of cigarette filter paper. Nevertheless, industrial implementation in paper and board converting industry has remained limited e.g. due to high investment cost and lack of knowledge and proven research results about laser systems reliability. Situation started partially change in late 1990´s when the lasers became cheaper and equipment performance and reliability was developed.

2. Background for the study

Research has shown that industry prefers to stay in their existing standard practices than change technology and solutions to something new (Ramsay and Richardson 1992), especially with technologies and new solutions that inherently have built in requirements for R&D and high investment costs required by change process. This study focused on examining and analyzing the different applicability innovation potentials in laser cutting of paper material, especially within complex geometry cutting application areas. It is known that laser cutting can be applied in many traditional fields and a high cutting quality is achievable with correct parameters. Ramsay and Richardson (1992) have shown that high cutting speed is achievable, when the laser power vs. cutting speed is correctly chosen. Hovikorpi et al. (2004) have shown that magazine paper can be cut with laser beam at speed of 4400 m/min which is very competitive with the current paper machine speeds (2000-2500 m/min). As this sort of detailed data does not seem to be widely available and large quantities, the aim of this study is to collect the sources of the information, refer to them, and then show the innovation potential of the laser cutting of paper materials compared to more traditional cutting methods. Aim of this study is to promote transition on conservative industrial sectors from old methods to more modern, faster and safer technologies.

The purpose and aim of this study is based on observation, that complex geometry cutting context is not widely expanded. This is so, even when the laser cutting technology is highly evolved, and as such in right side in the "hype curve" as Gartner, the one of leading information technology research presents it in evolution cycle of technology (see Fig. 1), the application areas in the complex geometry cutting context is not widely expanded. One possible reason for this small-scale use of lasers in paper material cutting might be a shortage of well-known and widely available research data about this phenomenon. Another restraint for use of laser for processing of paper materials might be the fear for possible coloration i.e. the yellowish and/or greyish color of the cut paper edge. This sort of coloration might appear during cutting or after the cutting, if the cutting parameters are not correct.

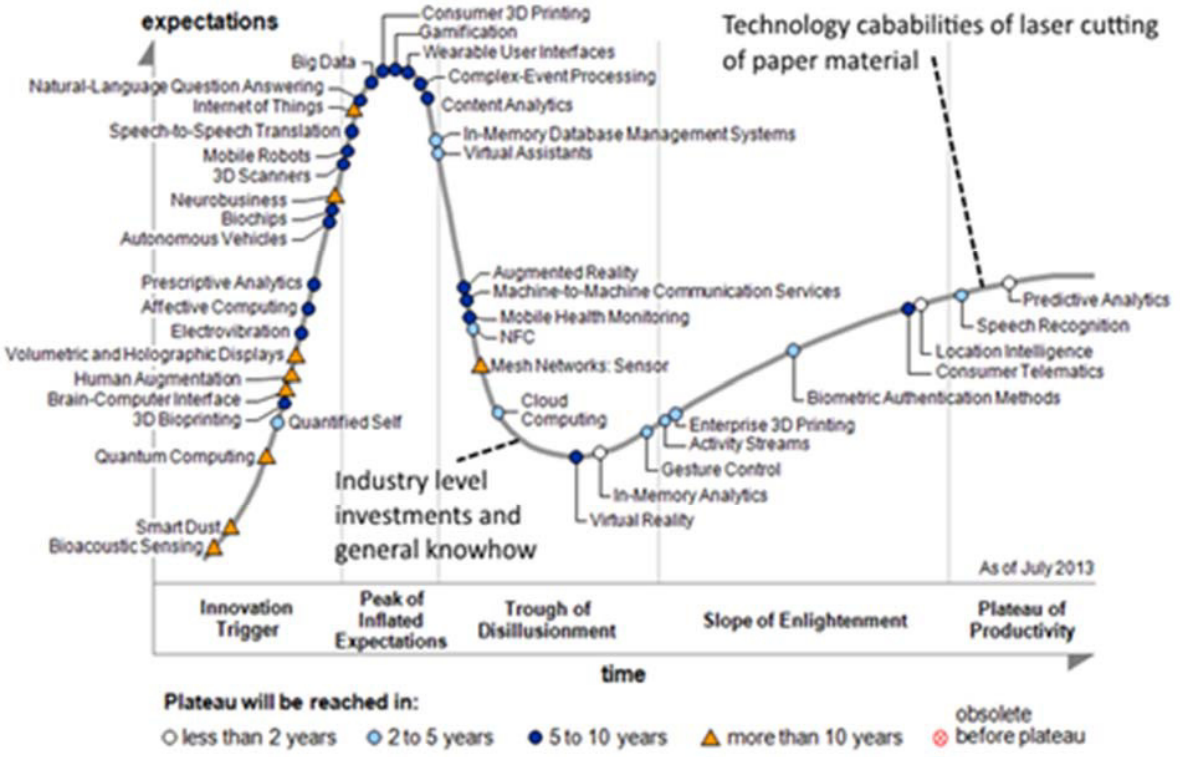

Fig. 1. Visualization of the separation on laser cutting capabilities and the knowhow of the potential available, based on general hype cycle*.

2.1. Technology for laser processing and cutting of paper materials

The laser cutting process of paper, as with most wood-based materials, is a thermo-chemical-decomposition process. The principle of laser cutting process applied to paper material is shown in Fig. 2. As the Fig. 2 illustrates, laser cutting of paper material is actually "direct evaporation" of solid paper material into gaseous products. The laser beam heats up the surface material of the work piece to temperature where chemical decomposition of material occurs (Steen 2003). The energy from the laser beam interacts with paper material and breaks chemical bonds and thus disrupt the structure of the paper material. When laser is used to cut a material such as paper, cardboard or pulp, this degradation process has the effect of reducing the large cellulose molecules down to their constituent which include carbon monoxide, carbon dioxide and hydrogen (Piili 2013).

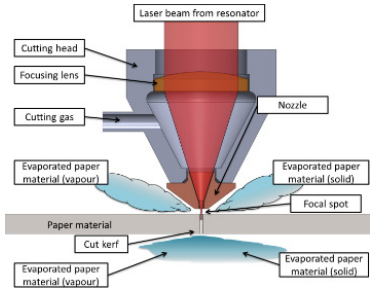

Fig. 2. Principle of laser cutting (Piili, 2013).

Conventional cutting of fibre material is mainly done by mechanical blade cutting or die-cutting (also e.g. rotating die-cutting tools are used too). High pressure water jet cutting became in 80's as a competitive method for paper edge

trimming, especially in large paper manufacturing processes. In 90's laser technology challenged these two older cutting mechanisms (Betts 2010), especially in packaging and paper converting industry (Malmberg et al. 2006). Progress and change challenge, on this market can be the industry investment preventing situation. In this situation a company has learned to live with the existing tools and their problems and is confident about their capability to run affordable production with their "own" familiar tools.

The challenge in this environment is that all new concepts have to be fully proven as working concepts, in these large scale environments. Few are ready to be a pioneer and as such it is tedious task to try to get new technology in these business areas. To succeed, a good information network is required and partnership between a system vendor and the companies has to be seamless. Because of these challenges, collaboration with each other might be the only working key answer for small and medium sized enterprises to excel in these sorts of change efforts. According to Westphal et al. (Westphal 2007), collaboration is an established option to deal with the increase in product and service complexity, dynamics of changes, requirements upon responsiveness and still crowing high quality demands. So, collaboration with universities and research projects is highly recommended as it gives smaller companies access in newest data and information in research. As example, laser cutting of paper material could potentially be a substitute for conventional cutting methods in following circumstances: production size is small or constantly below 1000 pieces, as part of processes with digital printing, high accuracy of complex geometries are needed, base material is expensive and maximum acquisition is needed, flexible production and fast delivery is needed and tailor-made products are the target (Malmberg et al., 2006).

Because of the advantages, laser cutting of paper material could potentially substitute conventional methods in many applications in paper and packaging related industries. Still wide availability of technological possibilities, e.g. as complex geometry cut paper products as a services, seems to be missing. In industry scale, various geometries for end product packages can and are cut using lasers, especially in case of medium sized batch productions. In small batch end user level, this method and its advantages do not seem to be available for individuals as a simple upload model and order type of services. There are services for end users to upload digital pictures or 3D models for paper and material 2D and 3D prints, sort of full blown self-service models, but similar ease of use services for laser cutting in comparative manner does not seem to available.

2.2. Practical application of laser cutting of paper materials

Considering the applicability of laser cutting for complex geometries with paper, different cutting tests have been done at the Lappeenranta University of Technology. E.g. laser cut rocking chair, double CD-package and the decorative chocolate wrap (shown in Fig. 3a-c) show some possibilities for practical products, art and design which can profit from laser cutting. For practical applications, in 1997 SIG Combibloc revealed a system, which allowed making of openings on the liquid food packages with partial laser cutting of packages where traditional perforation openings cannot be done (see Fig. 3d). Laser cut openings are very easy to tear and aseptic demands of packages are still filled (Brockmann 1999) and such laser cutting techniques are applied in industrial level, in this special context.

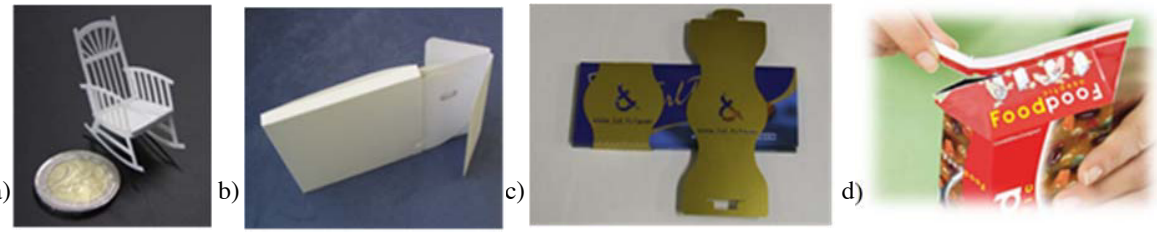

Fig. 3. (a) – (c) Examples of paper cutting potential in consumer goods industrial applications and (d) SIG Combibloc complete perforation commercial laser cutting application on liquid food packages[†].

[†] The Grocery Trader, 26.12.2010, SIG Combibloc introduces complete perforation for easy opening, source: http://grocerytrader.co.uk/?p=8421

As an example, laser perforation of cigarette tip is a laser processing method used to reduce tar and nicotine content in cigarette smoke (see Fig. 4). Operative holes can be made quite small and the size variation allows the laser perforated holes to be obvious or non-obvious. The smallest diameter for holes is 25 μm and the size can be increased depending on cigarette category. Also the shape of perforation can be round or rectangular‡. Besides being one of the first successful applications, laser perforation has also been one of those laser solution implementations that has replaced mechanical method almost completely (Bennett 2000).

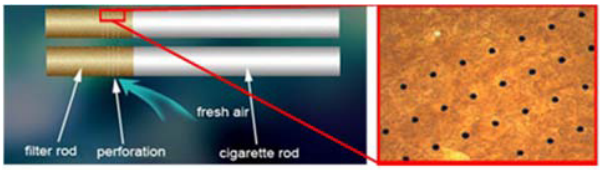

Fig.4. Cigarette perforation made by laser cutting (Brockmann 1999).

Laser processing of paper materials is also applicable for security purposes, e.g. for fabricating safety markings to legal and official documents. E.g. Fig. 5 shows safety marks. These markings are used in official documents (laser cut holes on a passport) to help the process of recognition originality of these documents.

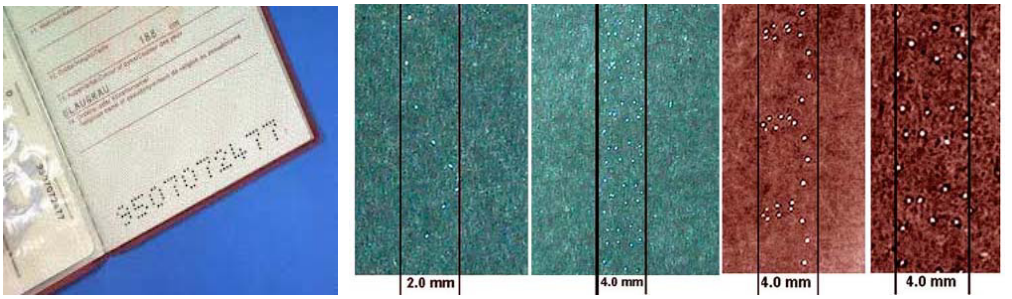

Fig. 5. Safety markings in official documents, made with laser§.

Laser cutting of paper materials is also widely used in non-industrial content, e.g. decorative cuttings for different applications for small-scale series production (see Fig. 6). All discussed examples of existing applications of laser cutting of paper material are either from a large scale industry cases or from special unique cases for somewhat small-series productions. It is clear, a missing business model seems to a possibility to buy unique or really small batch size laser cut paper design products, through simple and affordable service platform as an end user where the service would be offered through simple user centric web service, e.g. a service that would be comparable to ease of use of the services made for ordering paper prints from your own digital photos.

Based on the different application cases, it can be summarized that there is a large potential available for application of laser cutting of paper materials for complex geometries: Laser cutting can provide possibility for simple, fast and flexible design and manufacturing of unique packages, cards, flyers, ornaments and so on.

3. Aim and purpose of this study

This research studied and reports the potential and possible challenges in applying CO_2 laser cutting technology for cutting of paper materials in nowadays partially self-serviced supply chains where customer demand changing shapes, fast response and service in considerably rapid cycle. The study is focused on examining and analysing the

‡ Picture and perforation information: http://pdf.directindustry.com/pdf/rofin-laser-micro/laser-the-tobacco-industry/16106-350483-_2.html
§ Pictures and more details about official documentation perforation is available from, http://www.rofin.com/en/applications/laser_perforating/ and http://www.designforlasermanufacture.com/386/Laser_cut_holes_on_a_passport.html

different possibilities of laser cutting of paper material in application area of complex geometry cutting. The goal of this study was to analyse the feasibility of the laser cutting from technical, quality and implementation point of view and then showing up the possible business opportunities points. This study reveals some of business concepts and innovation potential of the laser processing for paper based materials like birch, pine, CTMP pulps, cardboard and recycled board.

Fig. 6. Card board based art work, achieved through laser cutting of the card board base material, Cardboard Safari**.

The study has been carried out, because even tough laser processing has shown many promising applications in many industrial context solution, there are still only quite few laser processing applications and/or services easily available for generic public, even in beginning of 2010´s when 2D and 3D printing applications are widely and easily available in multiple different solutions.

4. Methodology

This study builds on earlier research studies, where the basic knowledge and knowhow of the potential of laser cutting of paper material for complex geometries has been obtained. This earlier background research study was carried out using TRUMPF TLF 2700 carbon dioxide laser that produces a beam with wavelength of 10.6 μm with power range of 100-2500 W (laser power on work piece).

Experimental procedure in this study follows a path in which a background studies has been gathered from literature to collect and analyse the data and knowledge of current situation of laser cutting of complex geometries in current markets. This background information was combined with the knowledge of advantages and disadvantages of CO2 laser cutting. The knowledge and ideas were collected and analysed and the then ideas were feed in to the commercialization process model to build up the new business model concept to be able to reveal some of the industrial implementation and new service offering potential.

The analysis is based on well know success of laser cutting technology in general and in other industry areas and also the success of business models in those industries was considered. This knowledge was then applied in to the area of laser cutting of paper materials. In the end of the results paragraph, the success potential vs. risk of implementation is analyzed and the results of analyses are described in scale from 0 to 9. This scaling was done by laser cutting experts of LUT Laser research group. Value of zero represents huge risk in industrial implementation for example due to risk of economic factors. Value of nine represents good applicability and easy industrial implementation with excellent possibilities in business. The numeric value for the success potential is also illustrated with a graph and an explanation for the factor value is given.

5. Results and discussion

Based on innovation potential found out in the laser cutting of paper materials and the earlier background study made by Malmberg et al. (2006), a comparison of general advantages and disadvantages of modern CO_2 laser equipment for cutting purposes has been produced and it is shown in Table 1. As it can be concluded from Table 1,

** More examples of commercial applications of cardboard cutting are available e.g. in, https://www.etsy.com/shop/CardboardSafari

disadvantages of laser cutting are the relative high equipment cost and a need for highly trained personnel, which may restrict utilization of laser technology in new application areas. Potential of laser processing for paper material to cut complex geometries can be explained with the results of the background study and with the know advantages and disadvantages of CO_2 laser cutting.

Table 1: Advantages and disadvantages of CO_2 laser cutting of paper material

Advantages	Disadvantages
Tool-free production	High investment costs (vs. existing methods)
Dust-free production (clean working face)	Operators need to be specially educated
Noise-free production	Spare parts can be quite expensive
Reduced penetration of liquids	Smoke formation in cutting process
Geometry changes are easy, fast & flexible	Poor energy efficiency
Fast re-programming of the process	Harmful polymer coated paper cutting fumes

To analytically find the market potential and the current offerings, and to further do business potential analysis, a commercialization process model was created to describe the proof of concept models and to reveal the potential of paper material laser cutting process for industrial level for service applications (see Fig. 7).

As demonstrated in Fig. 7, the first step in commercialization process is the development cycle and study of the innovations introduced by laser processing of paper materials. Pilot products or services are generated in this stage. This part is followed by a second step, which is an industrial scale test and/or research and feasibility study. This is done to find the border limits for this innovation. The third step of the process is to analyze new business opportunities and then carry out techno-economical evaluation of potential industrial and consumer applications during the course of the development cycle. These evaluations provide basic information required to start the commercialization of the innovations. This ensures that each item on the business opportunity roadmap will be carefully checked out in terms of their economic viability. In this stage, research can support the commercialization of the innovation concerning laser processing of paper materials through establishing varied parameter research cases, supporting a start-up enterprise fast start phase and creating its business plan around the excising new technology knowledge.

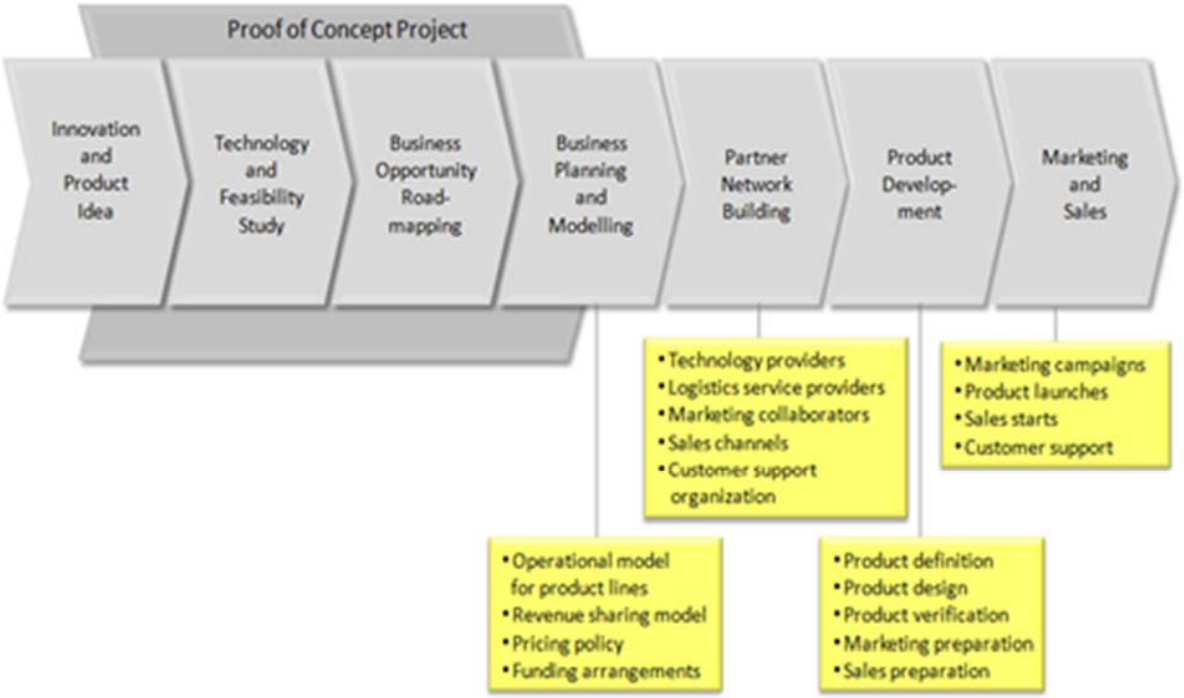

Fig. 7. Principal illustration of a commercialization process.

Considering what is already available in markets, as special solutions for laser cutting potential comparison is made into the 3D printing business area, which had transformed rapidly from high-end, high-cost services to web based printing service, offered in low price range as a service for everyone. Another comparison point is the nowadays easily available 2D digital photo printing services through internet based service solutions. The difference in these is that the 2D "printing" e.g. for 10*15cm paper photos has been really long time available, first in specialized photo stores, then in to grocery stores / markets and after that straight from Internet. For 3D printing, the services went almost straight to Internet services. The development of Internet and communications technology had a huge effect to this, as the communication and information exchange platform was already readily available, when the "boom" of 3D printing technologies started, roughly 10 years ago.

One important key factor could be to identify different interest groups in markets, in which some are services better than others, with current solutions offering. Several different interest groups, which one key group might have major role in building phase of these new business concepts, will need to be identified. In addition to that, there are many other things that have to be taken in account, e.g. for the case of laser cutting following things have to be taken into account:

- Customer readiness to adopt new services base on new, not so well known technologies.
- The possible actions of competitors trying to prevent the customer interest (e.g. false information and miss guided beliefs).
- Correct business configuration: e.g., a large enterprise as laser processing machine customer – SME sized companies and / or private customers as a large enough customer base for the enterprise.

When analysing different business opportunities in laser cutting of paper based materials, current market opportunities seem to lean more toward customer oriented and customized end products producing services. Customer orientation is extremely important for manufacturers as companies can achieve better coverage and profit by answering directly to customer needs (Ulrich and Eppinger 2004). Laser processing could offer a service model in customer orientation, available through internet, for end users with a good service quality as laser cutting can allow the service provider to have: short set-up times, high cutting speed, ability to do cutting in combination with digital printing, flexibility of series size and materials and low equipment maintenance costs (e.g. no tooling required). In general, laser cutting solutions in this business area are typically cutting systems for flat items (e.g. cutting sheet like paper and board materials) and flexible due to properties laser cutting can offer. In other words, these systems are real digital converters and part of digital manufacturing ecosystem. Even in digital manufacturing context, there needs to be viable pathway for industrial implementation from innovation process perspective. Pathway varies a lot in different business cases; so there is not a path that would solve all problems or one that would give success in every case.

In this concept, a customer uses a web service to order products based on customers own or out sourced design (similar to services for ordering 2D photo prints and 3D prints from Internet). The service provider combines large customer base under one service ecosystem allowing service provider to run laser cutting stations in high use levels to maintain high efficiency and productivity. This service provider could also provide more traditional 2D print variants and then combine these 2D prints to laser cut products. In addition one part of the service list is prints that are cut after 2D print process to deliver unique designs and product features requested by the customers. For this sort of business concept, a success potential (SF) value is given based on different aspects of usability potential of the laser technology. This evaluation is carried out by laser cutting experts on LUT Laser. Value of zero means the potential in the implementation is low and the risk level for failure is high whereas value nine means there is a very good possibility for success and failure risk is low.

1. Laser technology in this application area is quite unknown for large public. As a result, e.g. the number of laser cutting as a service for general public is small. Even though advantages are obvious and numerous (e.g. high cutting speed and cut quality), there are still the risks like the time period that technology application R&D project takes, before the actual innovative end solution is economically feasible. SF level 7
2. Different types of paper materials have different additives and their laser absorption ability varies. This can be a problem for laser processing of paper materials that will need special attention in research. Nevertheless, technology is generally reliable, only the properties of material have to be checked case by case. In addition, the material specific studies and research data is starting to be available in larger scale nowadays. SF level 6
3. The crucial part for applying laser technology to paper based end customer products is the quality of cut edges on paper materials. The research results support applicability as the laser technology has good properties in edge cut quality. SF level 8

4. High investment costs of laser equipment and optics related to it can be a risk, but generally speaking laser technology is reliable and "maintenance free" nature of laser equipment makes it an attractive tool when compared to conventional methods. Also possibility to carry out contact-free processing and possibility to process any geometry are the main advantages of laser technology. SF level 7
5. Performance of cutting speed in case of industrial implementation and special cases is promising. SF level 8

Occupational safety, in related to the laser technology, might be little lower compared to the conventional technologies. Laser technology is not as well known in all workplaces, which might increase resistance towards the change. SF level 5.

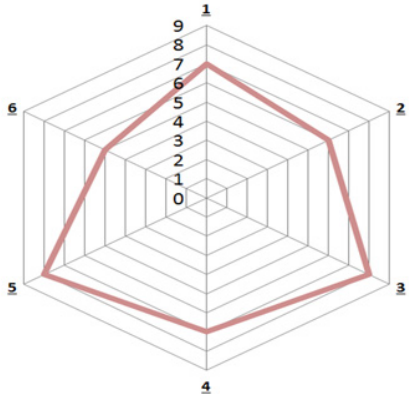

Fig. 8. Success factor analysis illustrated in graphic format. Axis numbers correlate into the above 6 different success factor analysis.

As the Fig. 8 shows, the success factors are quite high within these 6 analysis points. The lowest success factor is in the area of occupational safety, as the technology is new for people in the industry, which might result elevated risk for occupational hazards in start phases of implementation and use lasers in areas where people are used to work with only with conventional industry solutions. The highest success is predicted to be in the area of cut quality and in cutting speed performance. As it was shown in background studies, the cut kerf is exceptional good in laser cutting, as long as the parameters are correct. However, this success factor loses one point because of the challenge on getting the parameters just right is high.

The cut speed is related to the quality, as the quality is harder to get right with increased speed, but still even the medium speed is highly over the offering of the traditional methods. For the quality related challenges speed factor also loses one point. For the rest of the factors, the high investment cost, little awareness of technology for large masses and the possible need for R&D for materials changes are all costs driven and related factors and as such, because of the higher initial costs related on new technology, these factors have lost little more points.

6. Conclusions

This study relates on recent developments in laser technology, which has enabled new business model possibilities to emerge from technology capabilities. Nowadays high cutting speed can be easily achieved with high precision with laser technology. This is one key element in mass customization solutions, which was the key element in proposed business model. It means that lasers are potential tools to allow new services to emerge in commercial markets, for example considering the cut quality and cut speeds with paper based materials, both promise high success levels. Also the information revealed through this research study, including the knowledge of the aspect affecting the productivity and achieved cut quality, helps new product and service generation to come in this laser processing area. The study gathers information of this research area in one packet, where previous studies did not report findings as easy format as it is done in here.

The solutions and research data revealed that laser cutting of paper material has proven to have a strong commercial potential for consumer applications, for example in providing the small scale unique end result cut services for consumers. This innovative combination of current product genre with new product offering has the potential already,

but when this combination is applied further in future with techniques such as printed intelligence the full potential for completely new business opportunities can be achieved. On another hand, the pathway from idea to product and industrial implementation for new service based innovations, even with technology that has been around for tens of years can be very challenging. Considering what is already available in the markets, it would seem that one of the best possible business opportunities could live in platform business area. To be able to provide a platform that would connect private customer laser cutting needs into the machine owners, with a two way portal (a tool for machine owners to offer cutting services transparently to end customers and a tool for end users to easily purchase the service) might be the game changer. For analogy of this concept in 3D printing business area, think about Shapeways.

If the cut quality study phase is covered, the existing markets and competition has to be identified, and appropriate innovative and new business model needs to be developed. This will include the earning logic and the stages from production to delivery, with application of the technology. After business model generation, the related new products and services are designed. Typically companies do profitability calculations next, which help in the planning of the financing of the final product development and marketing effort.

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