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AUTHOR FINAL SUBMITTED VERSION

The Adoption of Additive Manufacturing Technology in Sweden

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Keywords: Additive Manufacturing, 3D Printing, Additive Manufacturing Processes, Design

Abstract:

This article analyzes the adoption of Additive Manufacturing (AM) technologies in Sweden. The dataset consists of a recent and representative sample of Swedish AM users (companies, universities, and research institutes). The authors investigate two questions. Firstly, what are the current applications of AM in Sweden (e.g. Rapid Prototyping (RP), production)? Secondly, what are the factors that can explain the variation in AM adoption among the users? Using a regression analysis technique, the main findings are as follows. (i) There is a variation among users' choice of AM application, and the majority of users are expanding their AM applications beyond rapid prototyping. (ii) There are two factors that positively affect the decision of firms to expand classical rapid prototyping and incorporate production and management as well. These two factors are using multiple AM technologies (as opposed to single Fused Deposition Modeling (FDM) technology) and being small companies. The authors discuss the implication of these results.

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Abstract

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Introduction

Additive Manufacturing (AM) enables the fabrication of components in a process where slices of a virtual model are created and produced in a layer-upon-layer additive building process. AM thus differs radically from traditional manufacturing which is either subtractive, where material is removed from a block of material, or formative, in which material is formed by a mold (which, itself, is manufactured through a subtractive process).[1] The technology has been adopted, since the mid-90s by most industries involved in product development as it is often the best method for quickly manufacturing prototypes. Until recently these technologies were unable to produce components of the same strength and quality as conventionally manufactured components. However, some of the latest technologies have advanced to the point where it is now possible, for certain types of components, to produce fully functional production components in a fraction of the time needed by conventional methods, particularly if one includes tooling/setup times. Rapid prototyping (RP) has thus evolved into rapid manufacturing (RM).[2,3]

It is believed that AM, as a manufacturing technology, is having an increasing role in many industries and that AM capabilities now cover various ranges of applications. But, according to the recent survey by Wohlers Associates, company's benefit from using AM to fabricate functional parts more than from other applications. The second most popular application is prototypes for fit and assembly. This indicates that the main advantage of using AM is in fostering product development processes by improving product quality, reducing cost (less assembly and tooling etc.), and reducing time to market, etc. The use of AM to fabricate production parts has also shown a continuous increase since 2003. In 2003 it was valued at 3.9% of the total global product-service revenues from AM, while this value increased to 42.6% in 2014. Besides this, the global market growth in the part production segment was 66% in 2014 to an estimated $1.748 billion.[4]

International approaches to AM are significantly different to that of Sweden. Governments in many countries (e.g. USA, New Zealand, Australia, UK, Germany, Singapore and China) are heavily investing in AM as a production technology, and deploying AM across their industrial sectors alongside partnerships with their research institutes and universities. One of the biggest challenges currently facing Swedish industry is a lack of the ability to adopt AM technologies and to deploy them to their full potential beyond just prototyping.[5]

Currently Sweden lies behind its neighbors Germany, the United Kingdom, France, and Belgium in its AM adoption rates, and is thus lagging behind on its capacity to innovate and keep up with similar industries in other countries.[5,3] International competitors in many sectors are continuously investing in AM, and the authors of this article thus believe that Sweden needs to strategically reduce the current gap on the lack of knowledge and implementation of AM. The authors also believe that the ‘’Swedish Agenda for Research and Innovation Within AM and 3D Printing’’, which was recently coordinated in 2014 by Umeå University in Sweden, is a great start to that path. According to the agenda, Swedish industry has adopted and utilized AM comparatively little beyond prototyping, and the infrastructure level in Swedish universities are well below the rest of Europe and worldwide.[5]

The above-mentioned Agenda is quite general, particularly concerning *why* Sweden is lagging behind in adoption of AM and also what factors can explain and predict the plausible move beyond using AM solely in rapid prototyping. This can be a problem from the perspective of users and policy makers in Sweden, because the agenda provides little insight on *how* to reduce the gap between Sweden and other advanced countries. This article, therefore, aims to provide a more detailed perspective regarding the current status of AM adoption and utilization in Sweden. The purpose of a more detailed perspective here is to act as a starting point in creation and delivery of knowledge and awareness on how AM can broaden the Swedish organization’s competiveness and service offering on a global market, how to add value to the Swedish companies products, and increased use of AM as a production technology. From this the authors believe it will be possible to be competitive and be able to produce high value and complex products in Sweden and keep this type of manufacturing in Sweden. This may enable some of the manufacturing activities and jobs to be brought back to Sweden. In order to initiate this starting point, this article investigates two questions: Firstly, what are the current applications of AM in Sweden (e.g. rapid prototyping, production)? And secondly, what are the factors that can explain the variation in AM applications among the users? The dataset consists of a recent and representative sample of Swedish AM users (companies, universities, and research institutes).

The rest of the article is as follows: The first section below provides a literature review of AM state of art in particular related to AM applications, AM technology types and raw materials. Then, the materials and methods section first introduces the research design (e.g. data collection method), and then specifies the method (empirical strategy), which is regression analysis. The results section provides the results in two sequences: description of analyses, and empirical result. The following section provides a discussion on the results, and the conclusion section summarizes the article outcomes' impacts and points out suggestions for future research.

Literature Review

This section provides a review of literature in order to identify the additive manufacturing (AM) technology types, raw materials types, and AM application areas worldwide and in Sweden.

Innovation in production technology is viewed as a powerful competitive weapon, which, if an industry adopts and implements it strategically, can bring about many other competitive advantages (e.g. superior quality, shorter delivery cycles, lower inventories, shorter new product development cycles).[6] Utilizing innovation in production technologies, such as AM, can cause improvements in market share. There are a few cases of research and R&D which propose that the management of the adoption and implementation of innovative production technologies is a distinctive area of study in research.[7] For example, in recent years the emergence of enterprise resource planning systems (ERP) and radio-frequency identification technology (RFID) has created extensive investigation and research articles on their implementation in academia and industries. The results of this are the creation of many process models and frameworks to assist decision makers and managers to implement those new innovations successfully. However, the research and practice of AM as a production technology has stayed relatively behind in its exploitation level.[8]

Besides the Umeå Agenda, which the authors address in the introduction section, there are relatively few scholars investigating current AM state of art or practice in Sweden. For example, Kianian et al 2015 share the same opinion as the Umeå Agenda concerning the level of adoption and deployment of AM in Sweden. Kianian et al 2015 also provide a few examples as exceptions to the lack of AM utilization in Sweden which are excellent examples of personalized high-tech manufacturing, which consists of a high content of technology, innovation and customized design.[9]

AM applications worldwide are well summarized by figure 1 below and, as noted earlier in the introduction, AM is having an increasing role in many industries, and AM capabilities now cover a wide ranges of applications. However, according to the recent survey by Wohlers Associates, companies benefit from using AM to fabricate functional parts more than from other applications. The second most popular application is prototypes for fit and assembly.[3]

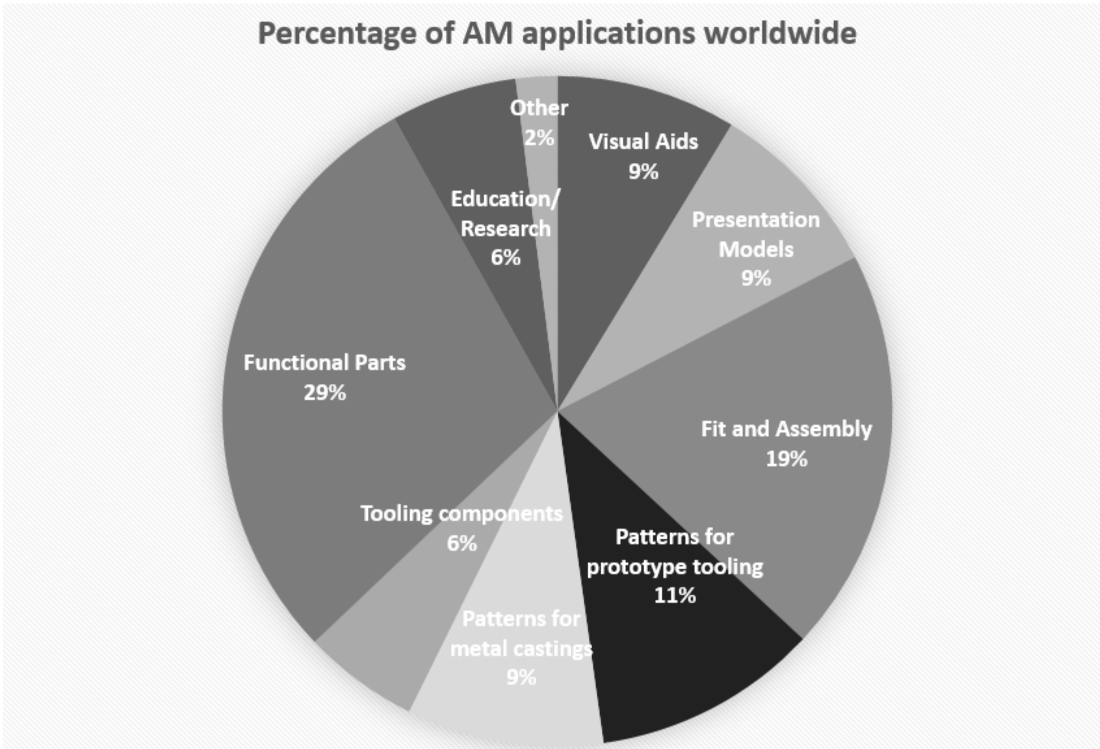

Figure 1. Percentage of AM applications worldwide

The authors categorize AM applications for this article's analysis into five categories in line with the Wohler's report classification in figure 1. The five categories are:

- Rapid Prototyping (RP): includes general prototyping applications, and patterns for prototyping tooling, pattern for metal castings, fit and assembly.
- Production: This category consists of functional parts and tooling components.
- Management: The management category includes visual aids and presentation models.
- Research & Development and Education (R&D and Edu): Includes fundamental science and research work in AM.
- Rapid Prototyping & Production and Management (RP & PROD and MNG): includes all the AM applications used by a single user (see the table 1).

There are many approaches to classifying AM processes, like categorizing them according to a baseline technology such as whether the process utilizes UV lasers, extrusion technology, printer technology, etc.[10,11] Another way is to classify AM processes together based on the type of raw materials (e.g. polymers, metals, ceramics) the system uses.[12] As Gibson et al 2010 argued it is more appropriate to use more than one classification method, as there are some issues with relying merely on one AM process classification. One of the issues, according to Gibson et al 2010, is that some of the AM processes with similar fabricated parts are placed in separate categories, and that some processes gather in the same categories in an odd way. There are some attempts to address these classification problems through the classification method proposed by Pham 1998, which categorizes AM processes based on both a technology baselines and raw material types.[13,14] This article's authors carefully consider these AM processes classification approaches, and then propose six categories for AM technology types, and four categories for AM material types. These classifications are shown in table 1 (Variable names and descriptions) in an empirical strategy section.

The authors in this article classify the Swedish AM users' size class in line with the European Union's definition.[15] Thus, the three categories of small firms (employment range 1-15), Medium firms (employment 16-100), and large firms (employment range of 101 and more) are identified as explanatory variables (see table 1).

Materials and Methods

Research Design

This article is based on a quantitative research methodology. The data comes from a survey of 55 Swedish users of AM (e.g. companies, universities and research institutes), which was carried out by 3dp.se between 2013-2014.[16] The authors of this article also add data from 15 additional users which have not been considered in the survey. Therefore, a total sample of 70 users is obtained. The authors conduct regression analysis as an analytical tool in this article. Regression analysis is a statistical process for estimating the relationships among variables.[17] The authors describe regression analysis and this article's empirical strategy in the following section.

Empirical strategy

The main aim of this article, as noted earlier, is twofold: First, the article describes and maps the various applications of AM that are actually chosen and utilized by the users (companies and research institutions), and second, the article analyzes the determinants of such choices. The first part of the aim is descriptive in nature and the authors will explain this part in the description part of the analysis section. The second part of the aim is analytical in nature and regression analysis is used as the analytical tool. Regression analysis is commonly utilized in social science and medicine to analyze the effect of some potential explanatory factors on the phenomenon of interest.[17] The phenomenon of interest in this study is the choice of application of AM by users. The authors employ a multinomial logit model in order to investigate the determinants of various AM applications choices by users. Formally speaking, the probability that user *i* chooses AM application *j* is given by:

$$P_{ij} = Prob(Y_i = j \,|\boldsymbol{X}_i) = \frac{\exp(\boldsymbol{X}_i'\beta_j)}{1+\sum_{k=1}^{J}\exp(\boldsymbol{X}_i'\beta_k)} \qquad j = 0, 1 \text{ Or } j = 0, 1, 2, 3, 4 \qquad (1)$$

$$i = 1, 2, 3, \dots, 70$$

Where $\boldsymbol{X}_i$ is the vector of explanatory variables, β_j are a set of unknown parameters per each explanatory variable, capturing the effect of each explanatory variables on the probabilities of choosing each AM applications, and j is the AM applications that users decide to choose. Starting from the vector $\boldsymbol{X}_i$, it is composed of several explanatory variables, which, as discussed in the literature review section, are expected to have significant (positive or negative) effect on the choice of AM application. Specifically, these explanatory variables are as follows: the AM technology types that the users deploy, raw material types, amount of AM machine investments, size (number of employees) of the user, and the location of the user (for the exact definitions, see Table 1). As noted, β_j are unknown parameters but they can be estimated through a procedure called maximum likelihood estimation, which is the output of regression analysis. And finally, " *j"* can be coded in two ways. First, in a dichotomous way, i.e. it obtains value *j*=0 when user *i* decides to use AM only and exclusively for the rapid prototyping purposes, and it obtains value *j*=1 when user *i* decides to use AM not exclusively for RP. Second, in an extend version, while *j*=0 is still the same as dichotomous way, *j*=1 can be expanded as follows: (the new) *j*=1 is when firms decide to still have the AM for RP purposes but also utilize AM for production and management purposes, *j*=2 is when firms decide to use AM only in Production, *j*=3 is when firms decide to use AM only for management purposes (e.g. visual aids, presentation models), and finally *j*=4 is when firms decide to use AM only in research & development and education. This implies that in the regression analysis, there will be two alternative dependent variables. Both of them are measuring the phenomenon of interest, i.e. application of AM among users, but just in two different ways. Moreover, in either of dichotomous or extended version, the *j*=0 is considered to be the "base" category (choice). This means the result of the estimation for each *j* should be interpreted with reference to this base category. It should be noted that, multinomial logit model is valid if the assumption of independence for irrelevant alternatives (IIA) is not violated.

Table 1: Variable names and descriptions.

	Variable names	**Description**	**Type of variable**
Application of AM	*Rapid Prototyping (RP)*	Gets value 1 if user only uses AM in RP, 0 otherwise	Dependent variable
	RP & PROD & MNG	Gets value 1 if user only uses AM in RP plus production as well as management, 0 otherwise	Dependent variable
	Production (PROD)	Gets value 1 if user only uses AM in production, 0 otherwise	Dependent variable
	Management *(MNG)*	Gets value 1 if user only uses AM in Management, 0 otherwise	Dependent variable
	R&D and EDU	Gets value 1 if user only uses AM in education & Research, 0 otherwise	Dependent variable
Technology Type*	*FDM (base)*	Gets value 1 if user has FDM technology in their AM, 0 otherwise	Explanatory Variable
	Polyjet (ColorJet printing)	Gets value 1 if user has Polyjet technology in their AM, 0 otherwise	Explanatory Variable
	SLA	Gets value 1 if user has SLA technology in their AM, 0 otherwise	Explanatory Variable
	SLS	Gets value 1 if user has SLS technology in their AM, 0 otherwise	Explanatory Variable
	Multiple AM Technologies	Gets value 1 if user has Multiple Technologies in their AM, 0 otherwise	Explanatory Variable
	Other AM Technologies		Explanatory Variable
ial	*Polymers (base)*	Gets value 1 if user has polymer as the material in their AM, 0 otherwise	Explanatory Variable

	Metals	Gets value 1 if user has Metals as the material in their AM, 0 otherwise	Explanatory Variable
	Multiple Materials	Gets value 1 if user has multiple materials in their AM, 0 otherwise	Explanatory Variable
	Others		Explanatory Variable
	Machine investments**	The amount of investment in 3-D machines ranges from 1 to 5	Explanatory Variable
Size class	*Small firms (base)*	Employment range of 1-15	Explanatory Variable
	Medium firms	Employment range of 16-100	Explanatory Variable
	Large firms	Employment range of 101 and more	Explanatory Variable
	Location***	Gets value one if the firms is located in ne of Sweden's Metropolitan areas (Stockholm, Gothenburg, Malmö)	Explanatory Variable

* FDM (Fused Deposition Modeling), SLA (Stereolithography), SLS (Selective Laser Sintering), Multiple Technologies (When a firm decides to engage in various combinations of the following technologies simultaneously: Laminated Object Manufacturing - LOM, Electron Beam Melting - EBM, Plaster Based 3D Printing - PP, Multi-jet Printing - MJP, Digital Light Projection/Processing - DLP, Scan, Spin and Selectively Photocure - 3SP, Direct Metal Laser Sintering - DMLS), Others (When a firm decides to engage in only one of the above technologies)

** Scale 1 to 5 corresponds to following ranges in thousand kroners: 1 (5 to 15), 2 (16 - 100), 3(100 to 250), 4(250 to 1000), 5 (over 1 million sek)

*** The three metropolitan areas in Sweden are based on local labor market region (Funktionella analysregioner) (SCB, 2014).

Results

Description

In order to have a better understanding of how AM users utilize the technology in Sweden, this section provides some descriptive statistics. Table 2 reports the number of observations, mean, standard deviation, minimum, and maximum values for each variables.

Table 2: Descriptive Statistics.

Variables	Observations	Mean	Std. Dev.	Min	Max
APP*	70	.6571429	.4780914	0	1
FDM	70	.3714286	.4866755	0	1
Polyjet	70	.0857143	.281963	0	1
SLA	70	.0571429	.2337913	0	1
SLS	70	.0428571	.2039973	0	1
Multiple AM Technologies	70	.3571429	.4826171	0	1
Other AM Technologies	70	.0857143	.281963	0	1
Polymer	70	.7714286	.4229444	0	1
Metal	70	.0571429	.2337913	0	1
Multiple Materials	70	.1571429	.3665631	0	1
Other Materials	70	3.2	1.499758	1	5
Small Firms	70	.5857143	.496155	0	1
Medium Firms	70	.2142857	.4132886	0	1
Large Firms	70	.2	.4028881	0	1
Location	70	.4142857	.496155	0	1

* APP is the dichotomous version of the dependent variable.

Looking at APP (our dichotomous dependent variable), it is interesting to note that about 65% of users are using AM not exclusively for rapid prototyping (RP), but either using AM for RP together with other applications (such as in production) or exclusively in other applications. Further looking at the data reveals that the majority of these 65% users have not given up applying AM in their RP, rather they are using AM in RP together with production and management (about 41%), while only 6% are using AM exclusively in their production, 4% exclusively for management purposes (e.g. visual aids, presentation models) and about 14% for education and research purposes. When it comes to technology types, as expected, Fused Deposition Modeling (FDM) is the most popular type with 37% of users exclusively adopting this technology. What is perhaps surprising is that using “multiple technologies” is almost equally as popular as FDM, i.e. about 36% of users. When it comes to material types, the dominance is for polymer with about 77% of users using polymer raw materials. An interesting observation is about the size of the users, which adopt and utilize AM technologies. About 58% of the users are small organizations (1 to 15 employees) and the medium and large size organizations are about 20% each.

In order to obtain some initial understanding about the relationship between the phenomenon of interest (application of AM) and potential explanatory variables, Table 3 shows the correlation matrix, which essentially shows how much of the variation of each variable can be explained by another variable in the same direction (positive value) or in the reverse direction (negative value).

Table 3: Correlation Matrix.

	APP	FDM	Polyjet	SLA	SLS	MT	OT	Polymer	Metal	MM	OM
APP	1										
FDM	-0,32	1									
Polyjet	-0,10	-0,24	1								
SLA	0,05	-0,19	-0,08	1							
SLS	-0,14	-0,16	-0,06	-0,05	1						
MAMT	0,35	-0,57	-0,23	-0,18	-0,16	1					
OAMT	0,11	-0,24	-0,09	-0,08	-0,06	-0,23	1				
Polymer	-0,18	0,42	0,17	0,13	-0,05	-0,30	-0,44	1			
Metal	0,05	-0,19	-0,08	-0,06	-0,05	-0,06	0,58	-0,45	1		
MM	0,15	-0,33	-0,13	-0,11	0,10	0,42	0,01	-0,79	-0,11	1	
OM	0,09	-0,09	-0,04	-0,03	-0,03	-0,09	0,39	-0,22	-0,03	-0,05	1

Notes: MAMT: Multiple AM Technologies, OAMT: Other AM Technologies, MM: Multiple Materials, OM: Other Materials.

Based on the Matrix, it is clear that some technologies and material types may hinder the expansion of AM to include other types of applications such as production. An example is FDM, which has negative sign in the correlation matrix (-0.32). This means 32% of the variation of AM applications toward using AM exclusively for RP can be explained by employing FDM. On the other hand, some variables show positive correlation sign. An example of this is multiple AM technologies (+0.35). This means adoption of multiple AM technologies alone can explain the expansion of AM applications to include production and management by 35%.

Empirical Result

Although the correlation matrix provides some initial understanding about co-variation of variables, a proper understanding regarding the effect of explanatory variables on the phenomenon of interest is obtained by conducting regression analysis. As discussed in the empirical strategy section, a multinomial regression model is used to estimate the effect of each potential explanatory variable on each AM application's option that users determine. Table 4 reports the estimation results.

Table 4: Determinants of Applications of Additive for users

Explanatory Variables	**Other departments than only DP (1)**	**Other departments than only DP (2)**			
		DP plus PROD & MNG (2.1)	**Only PROD (2.2)**	**Only MNG (2.3)**	**Only EDU (2.4)**
Polyjet	0.123	0.065	34.920	-20.766	-18.209
	(0.618)	(1.127)	(22,453)	(17,616)	(12,115)
SLA	0.717	0.952	37.952	-18.285	47.720
	(0.741)	(1.333)	(10,828)	(64,521)	(50,091)
SLS	0.088	-19.445	141.822	-21.904	1.344
	(0.912)	(17,658)	(44,234)	(32,996)	(2.285)

Multiple AM Technologies	1.581**	2.416*	74.710	-0.396	2.842
	(0.617)	(1.448)	(14,232)	(3.253)	(2.066)
Other AM Technologies	1.437	15.695	124.999	1.073	32.518
	(1.187)	(2,966)	(19,268)	(4,113)	(5,171)
Metals	-0.716	-16.163	-63.017	-0.602	17.860
	(1.143)	(2,966)	(3.630)	(4,113)	(3,762)
Multiple Materials	-0.208	-1.168	-1.434	-18.451	0.335
	(0.644)	(1.513)	(7,443)	(10,404)	(1.564)
Machine Investments	0.004	0.424	-35.175	2.185	-1.448*
	(0.167)	(0.385)	(5,982)	(1.479)	(0.795)
Small Firms	0.580	2.817**	64.220	21.291	-70.491
	(0.573)	(1.419)	(19,227)	(5,184)	(27,416)
Medium Firms	0.499	1.812	63.531	22.047	-1.195
	(0.569)	(1.400)	(23,87)	(5,184)	(1.618)
Location	0.062	0.403	2.053	3.489	-0.830
	(0.366)	(0.709)	(10,44)	(2.877)	(1.238)
Observations	70	70			

Notes: The Table reports the estimated parameters in Equation 1 (β_j) with standard errors in the parenthesis. The signs * and ** means the estimated parameters are statistically significant at 90% and 95% level respectively. The reference category for both model (1) and (2) are “using AM only in DP”. Model (1) is based on logit estimation (as a specific case of Multinomial estimation) and Model (2) is based on Multinomial estimation.

Table 4 shows the determinants of applications of additive manufacturing (AM) in various departments within the seventy user firms in Sweden. Model (1) is based on logit estimation (a specific case of the multinomial model) and model (2) is based on multinomial estimation. The results in model (1) shows that if a firm decides to use multiple AM technologies (as opposed to use only fused deposition modeling), then the firm tends to significantly use the AM in not only rapid prototyping, but also other departments. In model (2), the authors further break down such "other departments" into its components, as follows: (i) in rapid prototyping plus production and management (simultaneously), (ii) only in production, (iii) only in management, and (iv) only in R&D and education. These four breakdowns corresponds to models (2.1), (2.2), (2.3), and to (2.4) respectively in Table 4. It turns out that the observed significant effect of multiple AM technologies is associated with "simultaneously" using the multiple AM technologies in rapid prototyping, production and management departments. Using multiple AM technologies does not affect the probability of using AM exclusively in any of management, production, or R&D and education (relative to using the multiple AM technologies in rapid prototyping only).

Discussion

This section provides a discussion based on the results of the empirical analyses. The discussion is classified under two subheadings. Firstly, it describes the current applications of additive manufacturing (AM) in Sweden (e.g. rapid prototyping, production). Secondly, it investigates and analyzes the factors that can explain the variation in AM applications among the users.

The main findings of this article, based on using a regression analysis technique, are as follows. (i) There is a variation among users' choice of AM application and the majority of users are expanding their AM applications beyond rapid prototyping. (ii) There are two factors that positively affect the decision of firms to expand classical rapid prototyping and incorporate production and management as well. These two factors are using multiple AM technologies and being small sized companies.

Swedish Industry Trends in Additive Manufacturing Utilization Beyond Prototyping

AM capabilities are used in various applications and play important roles in many industries worldwide.[3] Sweden lies behind its neighbors (e.g. Germany, the United Kingdom, France, and Belgium) in its AM adoption rates and thus is lagging behind on its capacity to innovate and keep up with similar industries in other countries.[5] Despite all of these facts, the result of this article shows that the majority of the Swedish AM users (65%) are expanding AM capabilities beyond just rapid prototyping (RP) in order to take advantage of AM full potential. This outcome can be considered as a building block and indicates that Swedish AM users are starting to acknowledge that, as Sweden's international competitors in many sectors are continuously investing in AM, if Sweden wants to increase its global competitiveness, it needs to investigate means to redress its lack of ability to adopt AM technologies and to deploy them to their full potential beyond just prototyping. The increased use of AM will lead to an increased competitiveness for Swedish organizations in a global market, where innovation cycles are becoming faster and the demand for a decreased time-to-market is high. By the use of AM, the Swedish companies are able to shorten their innovation processes and are able to obtain added value to their products and services. Since the use of AM will enable the companies to manage the complete chain of the product, from innovation to manufacturing, all in-house, it will empower the possibility to maintain the manufacturing jobs in Sweden, For customized parts or parts in short series, this will help the Swedish enterprises to be able to compete on an international market.[9,16]

Factors Affecting Swedish Industry's Decision to Expand Beyond Rapid Prototyping

There are two factors that positively affect the decision of Swedish users to expand classical rapid prototyping and incorporate also AM production and management applications. These two factors are using multiple AM technologies and being small sized companies. When it comes to the former factor (technology types), fused deposition modeling, as expected, is the most popular type as 37% of users exclusively adopting this technology. What is perhaps surprising is that using "multiple technologies" is almost equally as popular as FDM, i.e. about 36% of users. When it comes to the latter factor, an interesting observation is related to the size of companies which adopt and utilize AM technologies. About 58% of the users are small organizations (1 to 15 employees) while the medium and large size organizations are at about 20% each.

Multiple AM Technologies

AM includes a range of technologies that offer advantages over traditional manufacturing. Until recently these technologies were unable to produce components of the same strength and quality as conventionally manufactured components. However, some of the latest technologies have advanced to the point where it is now possible, for certain types of components, to produce fully functional production components, in a fraction of the time needed by conventional methods, particularly if one includes tooling/setup times.[1,3] In addition to these technological advancements, there are some AM patents, which have been expired recently, and others that will be expiring in next few years. These facts foster the access to many AM technologies types, as both the technologies' cost reduces and upgrading process cycles shorten.

Small Sized Companies

Small enterprises and medium-sized firms are classified by their size, balance sheet or turnover.[15] Small and medium-sized enterprises (SMEs) represent the prominent portion of economic activities in Sweden, as about 99% of all type of enterprises are SMEs in Sweden.[18] Based on the result of this article, SMEs show to be the main driver of additive manufacturing (AM) adoption and utilization in Swedish industry. This is the result of the evidence in this study that the combination of small size users (58%) and the medium size users (20%) are the dominants AM users in Sweden (78%), as they show AM implementation beyond rapid prototyping. The authors believe that one of the main reasons behind this SMEs behavior is that AM removes existing performance trade-offs in two elemental ways. Firstly, AM decreases the initial capital needed to fulfill economies of scale. Secondly, AMs flexibility reduces the capital needed to fulfill economies of scope.[19] A reduction in the initial capital required is extremely beneficial to SMEs, as it enables them to try their ideas with lower risk. This increased use of AM will lead to an increased competitiveness for SMEs in a global market, where innovation cycles are becoming faster and the demand for a decreased time-to-market is high.

Other reasons that can describe the faster AM adoption by SMEs are as follow. AM adoption in a company will result in both operational and administrative structural change in the company. For example, production planning, process planning and quality control are some of those operational areas, which will be influenced significantly with AM adoption.[8] SMEs may also have a lower resistance to change when it comes to AM adoption as changes in their organizational structures and cultures, workforce skills may be less costly and less time consuming in comparison to large companies. The authors also acknowledge that SMEs cannot be treated as scaled-down versions of larger companies, and AM adoption's approaches that are generated for large enterprises might not be applicable for SMEs. Thus, the approaches for AM adoption and utilization are likely to be different between large companies and SMEs.[8]

Conclusion

During the analysis in this study care is taken in order to point out the reasons for which the explanatory variables are distinguished, and to also point out variables (e.g. multiple technologies, small firms) which may be common features to AM applications and implementations, all in order to provide a source for a potentially more generic solution.

Often it takes a lot persuasiveness to convince the management in an organization to change from the existing technology to a newer one. This is mostly due to the lack of technical knowledge of the various AM technologies available, and also the lack of understanding on how AM technologies can be utilized. Today, a reason for those barriers is the lack of skills in communicating the AM production capabilities, as the technique has moved from a prototyping technology to become full worthy manufacturing technology.[8] The authors believe that this article and its outcome can be considered as an initial attempt to address the issue above and it also can be used as a fertile ground for current AM users and also for those organizations, which study the potential of AM utilization in the future to understand the current AM adoption level in Sweden (as-is status).

It is essential to acknowledge the nature of this case study and the number of observations presented in this work. The scenario under investigation is limited to 70 AM users (e.g.

companies, universities, research institutes) in Sweden coming from various backgrounds. However, there are currently no statistics available on the total number of companies that use AM in Sweden. The authors expect that the effect and significance of this work outcome will be determined by the scenario under study. Therefore future works may look to extend the number of observations regarding the users of AM in Sweden. Another research opportunity will be comparing the various variables determining the AM applications and its implementations in different countries (e.g. Scandinavian countries). This can provide a better insight on where Sweden is standing against other countries when it comes to adoption of AM technologies. This is an important issue as initial investigations shows that Sweden is actually lagging behind the frontier in comparison with some other advanced countries. Therefore, such a systematic comparison between Sweden and other countries may help to convince the Swedish government of the importance of adoption of AM.

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Author Disclosure Statement

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References

1. Potgieter J, Diegel O, Noble F, et al. Additive manufacturing in the context of hybrid flexible manufacturing systems. International Journal of Automation Technology 2012; 6: 627–632.

2. Diegel O, Singamneni S, Reay S, et al. Tools for sustainable product design: additive manufacturing. Journal of Sustainable Development 2010; 3: 68–75.

3. Wohlers T. 3D Printing and Additive Manufacturing State of the Industry. Annual worldwide progress report 2014. Wohlers Associates Inc.

4. Wohlers T. 3D Printing and Additive Manufacturing State of the Industry. Annual worldwide progress report 2015. Wohlers Associates Inc.

5. Coming Together To Lead The Way. A Swedish Agenda For Research And Innovation Within Additive Manufacturing And 3d Printing. http://www.er.umu.se/digitalAssets/153/153181_vinnova_swedishagenda_additivemanufacturing3dprinting_2014.pdf (last accessed 03/25/2015).

6. Skinner W. Operations Technology: Blind Spot in Strategic Management. Interfaces 1984; 14: 116–125.

7. Voss C. A. Implementation: A key issue in manufacturing technology: The need for a field of study. Research Policy 1988; 17: 55–63.

8. Mellor S, Hao L, & Zhang D. Additive manufacturing: A framework for implementation. International Journal of Production Economics 2014; 194–201. doi:10.1016/j.ijpe.2013.07.008

9. Kianian B, Tavassoli S, Larsson T C. The Role of Additive Manufacturing Technology in Job Creation: An Exploratory Case Study of Suppliers of Additive Manufacturing in Sweden. 12th CIRP Global Conference on Sustainable Manufacturing-Emerging Potentials. September 22nd -24th 2014. Johor Bahru, Malaysia. Procedia CIRP in Elesevier; 2015. 26: 93–98.

10. Burns, M. Automated fabrication: improving productivity in manufacturing. Englewood Cliffs, N.J. 1993; PTR Prentice Hall.

11. Kruth J-P, Leu MC, Nakagawa T. Progress in Additive Manufacturing and Rapid Prototyping. CIRP Annals - Manufacturing Technology 1998; 47: 525–540.

12. Kai CC, Fai L K. Rapid Prototyping: Principles & Applications in Manufacturing 1998; Wiley.

13. Pham D, Gault R. A comparison of rapid prototyping technologies. International Journal of Machine Tools and Manufacture 1998; 38: 1257–1287.

14. Gibson I, Rosen D W, Stucker B. Additive Manufacturing Technologies Rapid Prototyping to Direct Digital Manufacturing. Springer, 2010 edition.

15. COMMISSION RECOMMENDATION of 6 May 2003 concerning the definition of micro, small and medium-sized enterprises. Official Journal of the European Union 2003; 36–41.

16. Kristiansson M. 3dp.se - News and knowledge of additive manufacturing, rapid prototyping and 3D printing. SURVEY: How to use 3D print in Sweden. 3dp.se (run by

AGI publisher). http://3dp.se/undersokning-sa-anvands-3d-print-i-sverige (last accessed 03/25/2015).

17. Wooldridge J. Introductory Econometrics: A Modern Approach. South Western College, 2009 4th Edition.

18. Teketel T, Berhanu Z. INTERNAL CONTROL In SWEDISH SMALL and MEDIUM SIZE ENTERPRISES. Umeå University, 2009.

19. Cotteleer M, Joyce J. 3D opportunity; Additive manufacturing paths to performance, innovation, and growth. Deloitte Review 2014; 14.

20. Swedish Agency for Economic and Regional Growth. Increased internationalization of Swedish companies. http://www.tillvaxtverket.se/sidhuvud/press/pressmeddelanden/pressmeddelanden/okadinternationaliseringblandsvenskaforetag.5.2fb5ad0e14c58098b74ea681.html (last accessed 04/25/2015).