UPPSALA
UNIVERSITET

Testbed for Material and Additive Manufacturing: Needs Analysis and Benchmarking

Brantnell, A., Salelkar, L., Linné, Å., Schliemann, M., Temiz, S., Lindahl, M.

Department of Civil and Industrial Engineering, Division of Industrial Engineering and Management, Additive Manufacturing for the Life Sciences Competence Centre (AM4Life) in cooperation with Region Uppsala

To cite this report: Brantnell, A., Salelkar, L., Linné, Å., Schliemann, M., Temiz, S., Lindahl, M. 2022. Testbed for Material and Additive Manufacturing: Needs Analysis and Benchmarking. Department of Civil and Industrial Engineering, Uppsala University: Uppsala.

Content

Executive summary

The manufacturing industry is facing a radical transformation due to digitization of production, demands on sustainable production, and possibilities of additive manufacturing (AM). AM, an alternative to mechanical manufacturing, provides several benefits such as rapid prototyping and low environmental impact. AM offers an opportunity for companies to improve their competitive conditions and value offerings while contributing to sustainable development. However, AM also poses challenges for companies, especially for small- and medium-sized enterprises (SMEs) as these companies often lack the financial resources and expertise to use new manufacturing methods. Testbeds are one way to support companies and accelerate change towards AM.

This report builds on previous investigations concerning testbeds and AM and explores the possibilities and conditions to establish a testbed with a focus on AM in the Uppsala Region. This report builds on site visits and interviews with ten existing testbeds and site visits and interviews with 14 companies. The testbeds were spread around the country, and the companies were centered on the Uppsala Region.

The findings are divided into two clusters: companies and testbeds. Altogether, nine companies either manufactured AM components or AM powder. All 14 companies had experience using AM, which is a clear indication that all these companies are early adopters or potential early adopters of AM. The companies that did not use AM (non-adopters) considered AM to be a promising technology but believed that AM did not fit with their current operations. The non-adopters believed AM was best suited for R&D, where proof of concepts and prototypes are developed and explored, which implies low technical maturity. Most the companies saw AM as a possibility for their operations. Non-adopters perceived AM as a possible complement to traditional manufacturing. Several non-adopters noted that they would adopt AM if customers requested it. Many non-adopters had difficulties identifying a business case for AM. In total, seven of the 14 companies had no experience with testbeds. Many companies envisioned a physical facility placed preferably near Uppsala and considered that a testbed could be helpful with material development. Many of the companies preferred a pay per use price model for the testbed. Furthermore, many of the companies were not willing to invest in creation of a testbed, but they were interested in using a testbed if available.

Of the ten testbeds investigated, six integrate AM in their operations. Irrespective of whether the testbeds used AM, the establishment of the testbeds can be seen as an incremental trial and error process, which takes time and often starts with common projects. The path to establishing a formal testbed varied across the testbeds, but all the testbeds were developed based on the needs of their stakeholders such as academia or industry. Most of the testbeds needed to secure financing. Many of the testbeds initially received public funding, and these funds were used to establish facilities and set up an

organization. The main challenge lies in having long-term financing covering running costs of rent, maintenance, human resources, and continuous investments. In addition to pay per use fees, a base funding originating (e.g., from member organizations) is crucial for long-term survival. The testbeds had difficulties estimating capacity use of the facilities, but all concluded the use is not yet 100%, so there are possibilities to increase the use of the facilities. It is clear that the testbeds need to define the value of the testbeds from a user perspective. Many testbeds experience challenges attracting SMEs irrespective of whether they focus on AM.

Based on the investigation, this report formulates one key recommendation: Create a joint testbed building on the existing AM competences and facilities in Uppsala by combining existing testbeds (AM@Ångström and U-PRINT) into one testbed.

That is, it is not viable to establish a totally new physical testbed as this would require several years of development and high investment costs. There are three main opportunities concerning this recommendation: 1) added value for Uppsala University and external users; 2) new user groups, and 3) specialization on life sciences.

Background

There are many signs that the manufacturing industry, globally as well as nationally, is facing a radical transformation due to several interacting factors. Increased digitization of production in design and construction, production and process control, as well as quality assurance and maintenance entail both major challenges and opportunities for the industrial companies. Furthermore, increased focus and demands on sustainable production within the supply chain as well as the expected radical transformation that AM entails accentuate further needs for change and development.

AM (often called 3D printing) is a production process where one layer at a time is added until the final product is achieved, which means that one can manufacture products, for example, with complex geometry and products with unique properties easier than traditional techniques where different production processes such as grinding, splicing, and milling are used to achieve the final product. There are several manufacturing techniques within AM such as stereolithography, selective laser sintering, fused deposition modelling, and photopolymer jetting [1]. AM is an umbrella term that describes the overall manufacturing process for these manufacturing techniques. All these manufacturing techniques have their own benefits and downsides. Stereolithography, for example, can quickly print objects with good resolution, but it results in rough surfaces and limited mechanical strength. Compared to traditional manufacturing, AM can save time if producing a few unique objects. AM can also reduce the environmental impact by, for example, minimizing waste in production and transport of material.

AM’s production processes and the use of new materials can address several of the 17 global goals for sustainable development such as goal 9 (sustainable industry, innovations, and infrastructure), goal 11 (sustainable cities and communities), goal 12 (sustainable consumption and production), and goal 13 (fight climate change). Therefore, AM can help companies improve their competitive conditions and value offerings while contributing to sustainable development.

However, new manufacturing methods such as AM also pose challenges for companies, especially for manufacturing SMEs, as these companies often lack the financial resources and expertise to absorb, incorporate, and sustainably use these new technologies and requirements [2]. To meet these challenges and capitalize on the opportunities of the new technologies, many companies, especially SMEs, will need external expertise in their development work in product, production, and market. One essential challenge is to transform the technologies’ opportunities into sustainable business, both in terms of investments in production systems and new customer offerings. A potentially important component for enabling and accelerating such a change is access to so-called testbeds where companies with low maturity in AM can assimilate such expertise and gain access to market-developing networks and competencies, a view that is in line with Vinnova’s definition of a testbed:

> A testbed is a physical or virtual environment where companies, academia and other organizations can collaborate in the development, testing and introduction of new products, services or other organizational solutions in selected areas.[1] (Vinnova, 2022)

The requirements for the testbed should, in line with Vinnova's financing criteria, include the following:

> • A testbed is or can be made available and open to users outside the testbed's own operating organization.
> • A testbed can be used for more than individual projects.
> • A testbed can be used for many products, services, processes, or users.
> • A testbed is not a locked display object or demonstration apparatus that cannot be adapted for testing new products, services, and processes.

Previous studies on testbeds and advanced manufacturing

Despite of the aim to support and develop competences among industrial companies in Sweden, previous reports in Sweden summarize some of the main challenges when establishing, developing, and using testbeds [3,4]. First, most testbed users are large companies as SMEs have limited resources. Second, the demand side of the testbeds have not been clearly identified and little focus has been put on communicating and marketing the potential value of the testbed to potential users. Third, the financing of the testbeds is usually managed though a mix of public and private money, but the long-term base funding seems to be challenging mainly due to the lack of fit with user needs. Fourth, facilities are not used to their full capacity–e.g., testbed facility use is around 55% in Sweden [3]. The use of testbed facilities, however, indicates a broad range of capacity use, from some facilities with almost no use at all to some testbeds having almost full capacity use. To this end, Tillväxtanalys [4] characterizes the establishment of testbeds as very challenging due to a "complicated process influenced by technological, organizational and institutional factors" (p.8).

There are also other investigations and reports of AM technology in the Swedish context. Focusing on AM technology in mid-Sweden, Valizadeh and Söderberg [5] identified several challenges for AM use. For example, suppliers have weak knowledge or no knowledge about AM technology and its potential. The study identified the need to develop initiatives to increase AM competences among various stakeholders in industry, regions, research institutes, and universities. The study also concludes the need to strengthen the AM competences not only regionally but also nationally and globally. Focusing on AM in the Uppsala Region, Strondl and Nilsson-Åhman [6] found that both the university and the companies in the region have competence and knowledge in material related to AM. The authors suggested further development and centralization of

[1] https://www.vinnova.se/en/m/testbed-sweden/

this material competence in a new AM center or a testbed focusing on AM. Also investigating the future need for AM, Strondl et al. [7] projected an increase in market demand and identified barriers to AM use. Some of the issues identified related to lack of an ecosystem for AM, quality assurance of AM, and lack of initiatives from industry concerning AM.

This report builds on the previous investigations and conclusions concerning the lack of ecosystem for AM and recommendations to establish an AM center/testbed in the Uppsala Region [6,7]. In 2018, Region Uppsala together with material sciences researchers and material companies in Uppsala, Sandviken and Stockholm joined forces in a Material X grant application (to Vinnova) to create a new industry region on the East Coast of Sweden with focus on materials and AM where Uppsala would be the center of this region. This collaboration resulted in the establishment of a network of actors from Region Uppsala, Uppsala University, and industrial companies in the regions. The application was ranked top five in the country but was not awarded a grant. This report builds on this established network of actors and takes a closer look at the potential of an AM testbed in the Uppsala Region.

Background to the task at hand

Based on the investigations mentioned above, there is a need to evaluate further the possibilities of establishing a testbed in Uppsala Region to support the transformation from traditional manufacturing to AM. In February 2021, Region Uppsala decided to fund a collaboration between Region Uppsala, Uppsala University (Department of Civil and Industrial Engineering), and Additive Manufacturing for the Life Sciences Competence Center (AM4Life) at Uppsala University to conduct a needs study. The needs study comprised four general aims:

1. To map and study existing testbeds in AM, and testbeds in advanced production and material in Sweden;
2. To map and identify companies' needs for a testbed in AM;
3. To identify conditions and interest in an Uppsala-based testbed in AM; and
4. To identify design aspects for a possible testbed in AM.

Based on the general aims, the following four questions were posed and answered.

1. What is/can a testbed be in practice? The companies were asked to provide their perception of a possible testbed, and the existing testbeds were asked to describe their testbeds.

2. Who should use the testbed? The companies were asked to provide their perceptions of testbed customers, and the existing testbeds were asked to describe their customers.

3.Why is it worth the investment? The companies were asked to provide their perceptions on the added value of a possible testbed, and the existing testbeds were asked to describe the added value of their testbeds.

4. How should testbeds be constructed and implemented? The companies were asked to provide their perceptions on construction and implementation of a possible testbed, and the existing testbeds were asked to describe the construction and implementation of their testbeds.

Advanced manufacturing and material companies

Altogether, 14 advanced manufacturing and material companies participated in this study. Tables 1 and 2 outline the key characteristics and main findings concerning the participating companies. Before talking about the main findings, some interesting observations can be raised concerning the company characteristics. **First**, almost all companies are older than ten years, which makes them established companies based on Family Business Institute definition of company age [8]. Only three companies (Exmet, Graphmatech, and Addnorth) were startups– i.e., younger than ten years–at time this report was prepared. Established companies often have more knowledge and experience than startups, which could mean that they are more prone to adopt new innovations. Also, existing for a long time often requires new thinking and adoption of new innovations continuously.

Second, three of the companies (VBN Components, Addnorth, and Exmet) had between 0 and 9 employees, which makes them micro-companies based on EU definition of company size,[2] and six companies (Graphmatech, OssDsign, Marine Jet Power, ESSDE teknik, Applied Nano Surfaces, and Piezomotors) had between 10 and 49 employees, which makes them small companies. One company (Österby Gjuteri) had between 50 and 199 employees, making it a medium-sized company. Three companies (Erasteel, Kanthal, and Sandvik) had more than 200 employees, making them large companies. Because large companies often have more resources than small companies, they are in a better position to adopt new innovations. On the other hand, large companies might be governed by formal structures and hierarchies, which could hinder innovation adoption. Small companies are often more flexible in terms of organizational structure and can think outside the box. This is one of the reasons that large companies like Apple create smaller organizations, independent from the larger organization, that can focus on developing new ideas and prototypes.

Third, although the companies represent advanced manufacturing and materials, they cover several different industries. Many companies focus on automotive and life sciences

[2] https://ec.europa.eu/growth/smes/sme-definition_en

but several other industries are covered such as metal, heating, marine, and space. As AM has applications in several fields from construction industry to life science, the industry segment is not necessarily the main aspect that can explain adoption. However, the technology readiness level of AM could differ between different industries. For example, the construction industry can print houses on-site with the available material [9]; therefore, the technology readiness level of this printing technique is presumably very high. In comparison, as the existing material properties and printing techniques are some of the barriers to print medicines [10], the technology readiness level is relatively low in this area. Next, we will outline the main findings concerning companies' views on and needs of AM and testbeds.

Table 1. Early adopters of AM

Companies	**VBN components**	**Erasteel**	**Graphmatech**	**Addnorth**	**Kanthal**	**OssDsign**	**Sandvik (Gimo)**	**Exmet**	**Cytiva**
Year established	2008	1992	2017	2016	1931	2011	1897	2017	Not disclosed
Revenues (latest fiscal year)	5 770	1 059 288	6 585	6 830	1 340 871	26 170	86 883 000	1 586	Not disclosed
Number of employees	8	377	10	9	298	47	38 666	3	Not disclosed
Company locations	Uppsala	Uppsala	Uppsala	Västra Götaland County	Västmanland County	Uppsala	Gimo	Stockholm	Not disclosed
Industry segments	Automotive, Mining, Aerospace, Defense, Racing, Confectionery and others	Metal industry	Automotive and others	Automotive	Industrial heating technology and resistance materials.	Life science	Cutting tools and service	Automotive	Not disclosed
Customers (some names)	ORKLA Confectionery & Snacks, SKF, US Armed Forces	High speed steel (no names disclosed)	Sandvik, ABB, National, Gränges, Addnorth, Wematter, Elonroad, Huber+suhner, RDC	Volvo Cars, Sandvik, ABB, Saab	Heating technology and materials (No names disclosed)	Assistance Publique – Hôpitaux de Paris (AP-HP), Vizientinc	Engineering & automotive (no names disclosed)	Volvo cars	Pharmaceutical industry and academia
Products/services (what they offer)	Metal powders, licensing solution, services like pre-studies, engineering & manufacturing services, and post treatment.	Conventional HSS, Powder metallurgy HSS.	Metal/Polymer graphene composite, services like licensing and customer development	Manufacturer of high-quality filament for 3D printing	Heating elements and electrification services	Regenerative solutions to patients with cranial or spinal bone defects	Extremely hard inserts	Development of amorphos metal components and licensing	Systems and consumables for research and development of pharmaceuticals

Table 1. Continued

Companies	**VBN components**	**Erasteel**	**Graphmatech**	**Addnorth**	**Kanthal**	**OssDsign**	**Sandvik (Gimo)**	**Exmet**	**Cytiva**
Manufacture AM components, powder, or services? (yes/no)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
AM experience (yes, some, no)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Perception on AM (Possibility or threat)	Possibility	Possibility	Possibility	Possibility	Possibility	Possibility	Possibility	Possibility	Possibility
Customers request AM (yes/no)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Indirectly*
Clear need for AM (yes/no)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Experience of testbeds (yes/no)	Yes, depending on definition of “testbed.”	Yes (Swerim)	No	Yes	Yes	No	Yes	Yes	Yes
Preferred parts of value chain covered for a testbed	Post processing (Surface treatments)	Material development and material characterization	3D printing, heat treatment and material characterization	Material development	Material characterization, printing, post processing	Designing, printing, post processing	Material development	Material development	Entire value chain with emphasis on post processing.
Preferred price model for a testbed	Pay per use	Not indicated	Subscription	Pay per use	Pay per use	Pay per use	Not indicated	Pay per use	Pay per use

* Customers request products with certain capabilities where AM can facilitate, and thus they indirectly request AM.

Table 1. Continued

Companies	VBN components	Erasteel	Graphmatech	Addnorth	Kanthal	OssDsign	Sandvik (Gimo)	Exmet	Cytiva
Main stakeholders preferred in a testbed (name of stakeholders)	Uppsala University, KTH, Swerim	Not indicated	Sandvik, ABB, GE (Cytiva)	Not indicated	Not indicated	Not indicated	Not indicated	Uppsala University	Uppsala University, Region Uppsala
Preferred use for a testbed (prototyping, material development, etc.)	Material development, surface treatments, prototyping.	Material development and material characterization	Prototyping and material development and material testing	Material development	Quality assurance, material characterization	Designing, printing, post processing	Material development	Material development	Materials research and post processing
Willing to invest in a testbed (yes/no)	Yes	No	Perhaps	No	No	Yes	No	No	No
Interested in using a testbed (yes/no)	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 2. Non-adopters of AM

Companies	Österby Gjuteri	Marine Jet Power	ESSDE teknik	Applied Nano Surfaces	Piezomotors
Year established	1983	1987	1999	2007	1997
Revenues (latest fiscal year)	107 000	423 720	13 277	11 906	28 358
Number of employees	70	55	14	12	35
Company locations	Uppsala	Uppsala	Uppsala	Uppsala	Stockholm, Uppsala
Industry segments	Steel foundry	Marine	Life science, Space	Automotive	Diagnostics, semi-conductor industry, and advanced optical measurement.
Customers (some names)	Valmet, MJP, Brunvoll, Ovako, OilQuick, Max IV	M/S CINDERELLA II (Passenger)	Cytiva	Bosch	Steinmeyer Mechatronik, Ginolis, 3DHISTECH, Svekon
Products/services (what they offer)	Casting, machining, classification, control as well as painting and mounting of complete unitts	Waterjets and control	Internal mechanical workshops for external companies	Surface treatment technology and licensing	Motors, cables, software, and controllers based on piezoelectric effect.
Manufacture AM components, powder, or services? (yes/no)	No	No	No	No	No
AM experience (yes, some, no)	Some	Some	Yes	Some	Yes
Perception on AM (Possibility or threat)	Threat	Possibility	Possibility	Possibility	Possibility
Customers request AM (yes/no)	No	No	No	No	No
Clear need for AM (yes/no)	No	No	Yes	No	Yes
Experience of testbeds (yes/no)	No	No	No	No	No

Table 2. Continued

Companies	**Österby Gjuteri**	**Marine Jet Power**	**ESSDE teknik**	**Applied Nano Surfaces**	**Piezomotors**
Preferred parts of value chain covered for a testbed	Material development	Material development 3d printing post processing.	Entire value chain is crucial with emphasis on post processing.	Post processing	Materials research, 3D printing
Preferred price model for a testbed	Subscription	Not indicated	Not indicated	Pay per use	Pay per use and extra on material cost
Main stakeholders preferred in a testbed (name of stakeholders)	Sandvik	Sandvik, Cytiva, Graphmatech, Österbybruks gjuteri.	Uppsala University, Region Uppsala	Volvo (Cars, Trucks, CE), Scania, Atlas Copco, Epiroc, Sandvik, ABB, Bosch, etc.	Materials Department from Uppsala University Industrial Partners such as Sandviken
Preferred use for a testbed (prototyping, material development, etc.)	Material development	Material development and 3D printing	Post processing	Post processing	Prototyping and material development
Willing to invest in a testbed (yes/no)	No	No	No	No	Yes
Interested to use a testbed (yes/no)	Yes	Yes	Yes	Yes	Yes

Varied technical maturity concerning AM

Nine companies either manufactured AM components or AM powder as shown in Table 1. We call these companies AM adopters. The remaining five companies were non-adopters (Table 2). All the companies had experience with AM, which is a clear indication that all these companies are early adopters or potential early adopters of AM. The companies that did not use AM in their operations considered AM promising technology but not a fit with the current operations, as expressed by this company (all company names are anonymized):

> "Yes, absolutely it is so [that we would need to remodel our entire operations], and then, yes it can be, there can be different steps, you can supplement existing [operations] with it or you gradually peel off the old production method and just run 3D printing further and further, and then it is well maybe 20, 30, or 40 years away, I do not know, but it will be something new, and it is a new step, so to speak, it is not that you improve the existing technology a little, this is a completely new step, and I think it can be quite interesting at least to look at, because I think it will come as I said." (Company A)

Moreover, the non-adopters perceived AM to be at the R&D level, where proof of concepts and prototypes are developed and explored. This perception is in line with a low technological readiness level. Existing research has identified nine technological readiness levels [11]. Products and applications ready for the market focus on levels 7–9 (i.e., product demonstrated in the operational environment), and research and development often focus on levels 1–4 (i.e., proof of concept and prototype development) [11].

Interest in AM

Almost all companies perceived AM as a possibility for their operations (Tables 1 and 2). None of the non-adopters perceived that AM would replace the traditional manufacturing methods in the near future. Several companies among the AM non-adopters believed that the interest in AM should come from their customers, which at the moment was not the case. Indeed, all non-adopters expressed that their customers did not request AM. One company expressed this lack of interest from customers as follows:

> "I would say our technology is quite new for our customer. Yeah, of course, we have customers for a long time. And they're more interested in the product and the invention that we can do for them than discussing what kind of production methods we're using." (Company B)

Hard to define a business case for AM

Although there was some interest in AM and some experience with AM, many non-adopters had difficulties identifying a solid business case for AM:

> "…[M]y opinion is that the industry is pretty conservative. And it is quite possible that if you were to say well, but today we have this kind of Duplex steel, hey and hey, everyone has used it for a very long time and now we have something more exotic [a 3D-printed part] instead and this one weighs like 50 percent as much and it is just as strong. If so, that would be, all other things being equal, a huge advantage. But I do not know if a customer [would dare], if you dare." (Company C)

Difficulties identifying a business case reflects the low technological readiness level that the non-adopters referred to. In fact, defining a business case for a proof of concept is often not a viable idea since the concept first needs to be validated in a lab and then in an operational environment before commercial exploitation. To this end, not being able to identify a solid business case is something we would expect from technological readiness levels 1–4. Despite difficulties identifying a clear business case, some of the non-adopters still perceived that they had a clear need for AM in their operations (Table 2).

Varied understanding of and expectations on testbeds

The 14 advanced manufacturing and material companies had different understandings of and expectations for testbeds. Half of the companies did not have experience of other testbeds, as expressed by this company:

> "Not really, we haven't really looked into that. So, we haven't made any use of it. We try to, you know, have some collaborations on our own, not too specific, like testbed centers and so on. It may be with suppliers. It could mainly be with companies that's not the supplier but it could be a supplier and those but we don't have an experience of testbeds I will say." (Company D)

When talking about what a testbed could be, many of the companies envisioned a physical facility placed preferably near Uppsala. The majority of the companies considered that a testbed should help with material development. Also, many companies perceived that post-processing is an important aspect to cover and provide help with. Few companies considered that the testbed should cover the entire value chain (i.e., material development, design, process management, printing, post processing, business development), except business development. Many companies did not have a clear view of what a testbed could be and therefore they probably focused on the technological aspects, ignoring the fact that a testbed could also help with business development and commercialization plans. Generally, companies were interested in using the testbed for material development and post-processing. The majority of the companies preferred a pay per use price model for the testbed, but two suggested a subscription system. The majority of the companies were not willing to invest in creation of a testbed, but they were interested in using a testbed if available (see Tables 1 and 2).

Advanced manufacturing and testbeds

Another important aim of our study was to investigate several existing testbeds to understand how they had been developed and what challenges they experienced. These findings could guide and provide advice to planning of a testbed in the Uppsala Region. Ten testbeds participated in the study of which six integrated AM in their operations. Tables 3 and 4 outline the key characteristics and main findings concerning the participating testbeds. Table 3 summarizes characteristics for testbeds working with AM (Alfred Nobel Science Park, U-PRINT, AM@Ångström, Amexci, AM at Mölndal, and Swerim). We label these testbeds AM testbeds. Table 4 summarizes characteristics for testbeds not working with AM (BioVentureHub, MITC, Stuns Energi, and Testa Center). We label these testbeds non-AM testbeds. Before talking about the main findings, some observations can be raised concerning the testbed characteristics. **First**, the non-AM testbeds seem to be older (i.e., have a longer history compared to the AM testbeds). One reason for this is that AM is a relatively new technology although it has received increased interest during the last ten years, for example, publications in using 3D printing in drug delivery devices have increased from 334 to 1129 between 2010 and 2020 [12]. **Second**, the number of employees varies between the testbeds from a few to 25. **Third**, some of the testbeds (Stuns Energi and Alfred Nobel) are virtual platforms with no established physical equipment available for users. These testbeds mainly refer to themselves as “collaboration platforms.”

Four, some testbeds are company-driven testbeds– Testa Center (Cytiva), BioVenture Hub (Astra Zeneca), and Amexci (Wallenberg companies); one or several of these companies set up and support the testbed. **Five**, the majority of the testbeds are connected to larger companies (as members or partners in the testbed). **Six**, SMEs are less likely to use testbeds (except for Stuns Energi). This reflects the common notion that large companies have more financial possibilities to engage in testbed initiatives. **Seven**, all testbeds have direct financing from public sources (municipalities, regions, and the state), except Amexci, which still is indirectly connected to public funding through some of the projects at the testbed. **Eight**, two of the testbeds are owned by universities with the aim to attract researchers as main users (U-PRINT and AM@Ångström).

In the next sections, the main findings are presented concerning the ten testbeds.

Table 3. AM testbeds

Testbeds	**Applikationscenter in Mölndal**	**Alfred Nobel Science Park**	**U-PRINT**	**AM@Ångström**	**Swerim (Powder Materials and Additive Manufacturing)**	**Amexci**
Year established	2021	2011	2016	2019	2016	2017
Revenues for 2020 (SEK thousand)	Not available	18 266	Not applicable (research infrastructure)	Not applicable (research infrastructure)	248 281 (entire organization)	27 608
Company location	Mölndal	Karlskoga and Örebro	Uppsala University	Uppsala University	Stockholm and Luleå	Karlskoga
Type of users	Industry, manufacturing and research	Industry, academia	Researchers, hospital	Researchers, students, industry	Industry and researchers	Industry
Owner structure (i.e., who owns the testbed)	RISE	Owned by municipalities, region, and academia	SciLifelab, Uppsala University	Uppsala University	Owned by 80% Industry and 20% government through RISE	Owned by 12 Nordic companies
Funding from	Owner and partners, public and private funding	Owners	Owners	Owner	Users and research funding agencies	Owners
Leadership	Director and board of directors	CEO and Board of Directors	Director	Director & Advisory board	CEO and Board of Directors	CEO, COO, CSO and Board of Directors
Number of employees	20	5.5	4	3 (part-time)	10–15 full time employees (involved in the testbed)	25
Type of organization (company, non-profit org, etc.)	State-owned research institute	Company	Part of Uppsala University	Part of Uppsala University (Project)	Non-profit research institute	Private company
Physical or virtual	Physical	Physical and virtual	Physical	Physical	Physical (Stockholm) and virtual	Physical

Table 3. Continued

Testbeds	**Applikationscenter in Mölndal**	**Alfred Nobel Science Park**	**U-PRINT**	**AM@Ångström**	**Swerim (Powder Materials and Additive Manufacturing)**	**Amexci**
Industry focus	Energy, automotive, metals, marine, polymers, bio-based materials	Health, advanced manufacturing, intelligent systems	Academia, hospital	Research	Metal Research	Metal and polymer research, development and production
AM included in operations? (yes/no)	Yes	Yes	Yes	Yes	Yes	Yes
Offer (e.g., matchmaking, machinery, etc.)	Services for the entire AM journey, customized offers, and partnership	Matchmaking, support with funding applications	3D printing service	Equipment and user support for research and development	Metal material research, offer competence in research and equipment	Print a part, product development, increase skills, test materials
Parts of AM value chain covered	Material development, design, printing, and post-processing	Design, printing, post-processing, and business implementation	Design, printing and post-processing	Design, printing and post-processing	Alloy development, powder production, processing, 3D printing, post-processing and validation	Design, process parameter development, process management, printing, post-processing, and business development

Table 3. Continued

Testbeds	**Applikationscenter in Mölndal**	**Alfred Nobel Science Park**	**U-PRINT**	**AM@Ångström**	**Swerim (Powder Materials and Additive Manufacturing)**	**Amexci**
Price model	Pay per use and member fees	Do not charge for services	Pay per use (printing, research engineer, material)	Pay per use (printing, research engineer, material)	Pay per use and research program	Member fees and pay per use (print job, training, research project) based on a quote and invoiced at delivery
Main stakeholders	RISE, AddUp, Alfa Laval, Chalmers, Digital Metal, DNA.am, Ericsson, Höganäs, Materialise, Modul-System HH, MSC Software, Nikon Metrology Europe, RENA Technologies Austria, Ringhals, Siemens Energy, Volvo Cars, Volvokoncernen, Region Västra Götaland, Vinnova, European Regional Development Fund	Örebro Municipality, Karlskoga Municipality, Region Örebro, Örebro university (Holding company)	Uppsala University	Uppsala University	Alleima, Bodycote, Carpenter Powder Products, Erasteel, Höganäs, Kanthal, Linde Gas, MTC Powder Solution, Quintus, Sandvik Coromant, Siemens Energy, SSAB, Uddeholm, Vattenfall	Atlas Copco, Electrolux, Ericsson, ABB, FAM, Husqvarna Group, Höganäs, SAAB, Scania, SKF, Stora Enso and Wärtsilä.

Table 4. Non-AM testbeds

Testbeds	**BioVentureHub**	**MITC**	**Testa Center**	**STUNS Energi**
Year established	2014	2011	2018	1983 (STUNS foundation)
Revenues for 2020 (SEK thousands)	5 218[*]	12 478	12 723	20 000 – 49 999
Company location	Gothenburg	Eskilstuna	Uppsala	Uppsala
Type of customers	Industry	Industry, researchers, students	Academia and SMEs	Industry, researchers, local and regional authorities
Owner structure (i.e., who owns the testbed)	Owned by AstraZeneca	Owned by several companies and Mälardalens University	Owned by Cytiva	Foundation (owned by several parties representing the academia, local, and regional authorities)
Funding from	Owners	Owners	Owner	Owners and external projects
Leadership	CEO, boards of directors	CEO	CEO and Cytiva Board of Directors	CEO and Board of Directors
Number of employees	8–10	8	7 (no employees, all staff employed by Cytiva)	7
Type of organization (company, non-profit org, etc.)	Non-profit company	Company	Non-profit company	Foundation
Physical or virtual	Physical	Initially virtual, later physical	Physical	Virtual
Industry focus	Life science and biotech	Not specified	Bio-production	Energy & Environment
AM included in operations? (yes/no)	No	No (one project includes AM)	No	No
Offer (e.g., matchmaking, machinery etc.)	Labs and office space	Courses, workshops, matchmaking	Equipment and infrastructure for bio-production, support with funding, support with innovation development, education	Matchmaking, partner in externally funded projects

[*] Public financial support that BioVentureHub received during 2020.

Table 4. Continued

Testbeds	**BioVentureHub**	**MITC**	**Testa Center**	**STUNS Energi**
Parts of AM value chain covered	Not applicable	Not applicable	Not applicable	Not applicable
Price model	Not specified	Goodwill or consultancy	Pay based on the time spend in the labs and equipment used.	Goodwill or consultancy
Main stakeholders (name of stakeholders)	Partners: Astra Zeneca, Mölnlycke (medtech) IBM (IT), GoCo Health innovation, 30 SMEs in life sciences	Mälardalens University, Alfa Laval, Volvo Group Truck Operation, Hexagon Manufacturing Intelligence, Eskilstuna fabriskförening, Volvo Construction Equipment, Leax Group, Västra Mälardalens industriförening, Eskilstuna kommun, GKN Driveline	Cytiva, Uppsala University, SMEs, Swedish Government/Vinnova	Uppsala University, Uppsala County, Uppsala Municipality, SLU, Region Uppsala, Trade Chamber in Uppsala

Establishing testbeds through an incremental process

Irrespective of whether the testbed engages in AM, the establishment of the testbeds can be seen as an incremental trial and error process. That is, the testbeds were not established overnight as there was first a need to run projects involving several stakeholders. These projects in turn provided a basis for a testbed once a critical mass of projects was achieved involving various stakeholders. Achieving the critical mass often took several years. This type of incremental process, where knowledge and competence are gradually developed, can eventually lead to a formal testbed, as explained by one testbed director (the testbed names are anonymized):

> "So, at first you have a machine. [. . .] And eventually you create some knowledge, you create some competence, you create a critical mass, that can be the base for transforming [everything] into a testbed and that's how we have done it." (Testbed C)

The path to a formal testbed varies across the testbeds. For example, U-PRINT and AM @Ångström originate from research needs at Uppsala University. The Applikationscenter in Mölndal has been created based on the process and material competence at formerly Swerea IVF (now RISE) that worked closely with the manufacturing industry. Swerim is strongly connected to AM initiatives at the Swerim Research Institute with several decades of experience from industrial applications based on metals. MITC is based on the needs of the manufacturing companies in the region combined with the use of academic knowledge from Mälardalen University. MITC started as a virtual collaboration platform and evolved into a physical organization. Amexci was founded as a joint R&D organization involving 20 companies within the Wallenberg sphere based on the needs of the companies to increase their knowledge in the AM area. This is further explained by one testbed:

> "[The testbed] is, is grown from complete, or only an industrial interest. So, there are the industry and the interest from the industry that started this initiative. And then the industry decided to go together to do something instead of starting it internally in each company, which is a long way and also costly, and it takes time, and it requires a lot of competence." (Testbed B)

Stuns Energi has a 40-year history in Uppsala and it was established to increase the collaboration between the university (Uppsala University and SLU), the region (Uppsala), and companies in Uppsala. Testa Center was established by Cytiva to pursue development and testing of biological production through collaboration with students at Uppsala University and collaboration with SMEs in the region. A similar approach can be found in the BioVentureHub originating from the R&D organization of AstraZeneca with the aim to support collaborations with SMEs by offering labs.

Long-term financing

A challenge for the majority of the testbeds is securing financing. Many of the testbeds initially received public funding and these funds were used to establish facilities and set up an organization. The main challenge lies in having long-term financing covering running costs of rent, maintenance, human resources, as well as continuous investments. For the testbeds involved in AM, the initial cost of developing and establishing the testbed has been higher compared to traditional manufacturing tools, facilities, and machinery due to the high cost of machinery, especially the 3D printers for metals.

Usually, the testbeds use a variety of funding sources. Several of the testbeds have membership and partnership agreements with large industrial companies (MITC, Amexci, and Applikationscenter in Mölndal). These companies pay an annual membership fee and are given a position on the board to influence the future development of the testbed. These companies also pay per use. Thus, it seems important for testbeds to involve large companies with deep pockets to secure the base funding. Moreover, the regions are also actively funding several of the testbeds (MITC, Stuns Energi, Alfred Nobel Science Park, and BioVentureHub). The regions seem to provide three types of funding: an annual lump sum, funding for fixed costs such as office buildings, and one-time grants. In several cases, universities also fully or co-finance the testbeds (MITC, U-PRINT, and AM@Ångström). U-PRINT and AM@Ångström are both located in, owned, and financed by Uppsala University. MITC has been organized as an association outside of the Mälardalen University to avoid the high overhead costs within the university. Some testbeds (Swerim and Applikationscenter in Mölndal) are owned and partly financed by public research institutes.

To establish long-term sustainable financing, the testbeds have put much effort in developing how to charge for their services such as membership fees combined with pay per use. Alfred Nobel Science Park, however, did not find a suitable way to charge for its AM services and had no memberships fees for base funding; it was forced to close down in 2022. The financing issue and the possibility to combine various funding sources is reflected by one of the testbeds:

> “And base funding basically means foundational funding, not connected to a project not connected to certain targets as loose money as you can find. [. . .] And then make sure that you use every krona [SEK] to co-finance other projects. So, you don’t just oh no, we paid one person it cost a million and now that million is gone. Make sure every krona [SEK] becomes two or three.” (Testbed A)

Thus, yearly base funding is critical for the survival of the testbeds in combination with additional financing through individual projects as well as member fees and/or pay per use. The suggestion from one company-driven testbed is to clearly identify what users can pay for services and let that direct the future testbed and the enrollment of main stakeholders.

Testbed users

The testbeds had difficulties estimating capacity use of the facilities but all concluded the use is not yet 100% and therefore there are possibilities to increase the use of the facilities. Clearly, the testbeds need to define the value of the testbeds from a user perspective, a view that is also emphasized by the testbeds when discussing key challenges. For the testbeds involved in AM, it seems that the testbeds focusing on users from academia (i.e., researchers and research groups such as U-PRINT and AM@Ångström) have highly skilled users in relation to AM. The users are aware of the possibilities with AM, and the researchers themselves can run the machines if necessary. For the testbeds focused on industrial users, the level of AM knowledge and competence among users seems to vary a lot. Many of these testbeds offer broad services including training to companies, including seminars to inform and communicate about the potential of AM technology, especially in trying to attract more SMEs to the testbeds. Some also provide more customized services to their users, depending on their needs and knowledge of AM.

In general, there are some challenges in attracting SMEs to the testbeds irrespective of whether the testbeds focus on AM. For example, as the majority of the testbeds have been developed in close collaboration with large companies (as partners and members), the testbeds are designed to fit the challenges of large companies and not the challenges of SMEs per se.

Reflection and implications of the investigation

The investigation reflects some of the issues that previous reports have already pointed out [3,4,5,6,7]. For example, the 14 investigated companies had a vague opinion of what a testbed is or what it can be, which reflects that existing testbeds have problems communicating their roles to potential users. Moreover, the investigation also confirms previous findings that testbeds tend to focus on large companies and find it difficult to attract SMEs, although the idea behind testbeds are to support SMEs in particular [3]. Many companies involved in the study had no or little knowledge about AM, although some were involved in AM and saw some potential in establishing a testbed focusing on AM. In accordance with Tillväxtanalys [4], it is evident that the establishment of a testbed is in itself challenging and it takes time to build a critical mass of projects and competence before it is even possible to establish a formal testbed.

In this report, four specific questions were raised and addressed. Below, we will summarize the answers to these.

1. What is/can a testbed be in practice?

The majority of the companies had little experience with testbeds. The companies envisioned a physical facility placed preferably near Uppsala. Companies wanted a testbed to cover certain parts of the AM value chain such as material development, printing, and post processing. Material development was essential for many companies. Some companies envisioned testbeds as a way to bridge the gap between research findings and commercialization. Some companies perceived that a testbed could be a good way to connect people and share knowledge, but many companies did not have a clear view of what a testbed could be.

In general, the testbeds were established quite recently (during the last ten years). Many of the testbeds build on a collaboration between government, universities, and industry. The majority of the testbeds have a physical facility with employees and equipment. The initiative to establish the testbeds came from companies, regions, or universities. The testbeds focused on creating value for their customers. The objective was not to make money but to contribute to industrial development. The majority of the testbeds were run as non-profit organizations and were working with different parts in the AM value chain. The majority of testbeds provided support with design, printing and post-processing, and some provided additional support such as material development and process management.

2. Who should use the testbed?

The companies perceived that a testbed could be relevant both for SMEs and large companies. The companies envisioned several possible sectors for a testbed such as life sciences, energy, automobile, marine, and space. As Uppsala is often perceived as a life science region, several companies reflected on that. However, many considered that the focus could be broader than the life sciences.

All of the testbeds targeted companies, mostly local companies, and universities from various industrial segments: aerospace, energy, automotive, general manufacturing, tooling, and hospitals.

3. Why are testbeds worth the investment?

Many companies perceived testbeds as part of a possible long-term strategy rather than a tool used for short-term needs. Still, companies assumed that their use of a testbed would initially focus on limited prototype development projects or in general explore the possibilities with AM. Some companies also perceived that testbeds could be good for both short-term and long-term needs. The companies that already applied AM in their operations had a clear understanding of how they would use a testbed. Some companies referred to their customers when reflecting on the use of a possible testbed and considered that the need for a testbed should come from their customers. Some companies perceived that customers do not care about how something is produced, so they are not interested in AM as a production method.

The testbeds were grounded on the needs of the involved stakeholders: companies, universities, and regions. The added value of testbed was related to shortening the time between innovation and market placement or supporting researchers to take the next step towards AM. Several testbeds were set up to expediate research through externalizing R&D in AM. One testbed (U-PRINT) also offered services to hospitals to enable rapid prototyping and preoperative planning. In addition to supporting R&D in different ways, testbeds were perceived as ways to build a community and disseminate knowhow, for example, concerning AM.

4. How should construction and implementation take place?

The companies mentioned some key players that could be included in founding a testbed: university, Region Uppsala, and companies in general. The companies were hesitant to invest in building up the testbed before identifying a clear business case and establishing return on investment. Some companies perceived that the founders should fund the testbed and users should pay per use whereas some companies preferred a subscription system. Some companies had ideas on how to organize the management of a testbed, but many had not considered how to manage a testbed.

The existing testbeds are funded by the involved stakeholders, often government and companies. The majority of the testbeds had a management board and all of them have some employees. Depending on the activities and services offered, the number of testbed employees varied between three and 25. Some of the testbeds had a pay per use cost model where the customers pay per use or part. A base funding coming from partners or other sources was important for long-term existence.

Based on the investigation in this report, we have identified one main recommendation concerning possible establishment of a testbed focusing on AM in Uppsala. We have also identified three possibilities related to the recommendation.

Recommendation: Create a joint testbed building on the existing AM competences and facilities in Uppsala by combining existing testbeds (AM@Ångström and U-PRINT) into one testbed.

That is, it is not viable to establish a totally new physical testbed as this would require several years of development and high investment costs. The investigation includes two existing testbeds in Uppsala, U-PRINT and AM@Ångström, both belonging to Uppsala University. Both testbeds focus on and originate from research and have invested in a number of 3D printing machines. The testbeds have engineering competence with focus on two different but complementary areas: 1) printing and services for medical research, mainly in polymer with strong connection to Academic Hospital in Uppsala (U-PRINT) and 2) printing and testing of new materials, mainly using metal powders with a strong focus on research applications (AM@Ångström). Also, both testbeds have existing users of their facilities and have identified a need among the research community within

Uppsala University and in clinical use at Akademiska Hospital. The knowledge level of AM among these user groups is very high compared to many of the 14 companies included in this report.

Thus, our suggestion is that U-PRINT and AM@Ångström combine their resources into one testbed, which will require joint coordination of facilities and sharing costs and competences under the ownership of Uppsala University. This is, of course, not a quick fix due to the complexity of the involved testbeds. Based on our investigations it is not possible, in the short run, to co-locate the two existing testbeds but combining resources in different ways is a viable option at the moment. We identify three main opportunities associated with the establishment of a joint testbed including U-PRINT and AM@Ångström.

Main opportunity I: Added value for Uppsala University and external users. The joint testbed will benefit both Uppsala University and the external users. For Uppsala University the joint testbed entails improved use of resources, new income sources, and consolidation of knowledge, which in turn contributes to a stronger AM ecosystem. For external users the joint testbed can facilitate contacts with the testbed (previously two separate testbeds) and consolidation of knowledge will contribute to a more comprehensive service towards users. The joint testbed can provide information about AM, summarize resources and competences in the region, list the services that the joint testbed could provide and offer different services relating to AM. Although physical co-location will not be possible in the short run, virtual co-location through a website or platform is. These activities will together enforce the AM ecosystem and facilitate AM adoption. However, to take advantage of the added value possibility long-term financing is an important issue to address. Pay per use will not provide a sufficient base funding for a testbed. How could this joint testbed be financed? At the moment, the both existing testbeds are funded by different stakeholders and creating a joint testbed would not require extensive new resources. If however, the joint testbed will be expanded towards new user groups long term financing is needed to cover these new operations. Long-term financing could come from Region Uppsala or some of the large companies in the region. However, companies were in general not interested in investing in starting a testbed, and Region Uppsala does not have large resources budgeted for a testbed.

Main opportunity II: New user groups. The joint testbed already has certain user groups of their services and facilities, which gives a good basis to build on and open up the joint testbed towards new users. AM@Ångström focuses on metal printing and their existing users are university researchers. U-PRINT focuses on polymer printing and their existing users are university researchers but also surgeons from the Akademiska Hospital. Opening up the testbed could be divided into two phases. During phase one, the testbed could be opened up and marketed for other academic/research groups outside Uppsala University. Also, it could be possible to expand the scope of clinical users at Akademiska Hospital. Starting with these two stakeholder groups would be feasible since there are early users from these groups that could inspire and show the way for other users. During phase two, the testbed could be opened up and marketed for start-ups from universities and companies that could benefit from AM. In the long run, there might be possibilities to develop annual memberships fees to provide base funding for the expanded operations. As the journeys of the existing testbeds show, projects can bring together important stakeholders and the stakeholders in turn might be willing to invest in a joint physical testbed in the long run. Whether this takes one or several years depends most likely on the benefits of AM for partners and the size of R&D budget of the partners. To open up the testbed it is important to work with business models, processes and regulatory aspects concerning AM, and clearly define the offer of the testbed including the competences, what is provided, how much it costs, and how it works. Uppsala University and the surrounding innovation system can help the testbed to address these and other relevant aspects.

Main opportunity III: Specialization on life sciences. We see the need for specialization and thus the testbed could focus on life sciences since the existing testbeds outside Uppsala do not focus on this industry segment. As Sweden is a small country, we see the need to connect a new testbed to similar activities nationally and to other testbeds involved in AM. How could the testbed in Uppsala complement other AM testbeds? Focusing on life sciences would be one feasible approach to complement the other testbeds and also build on the key competences in the Uppsala Region with medical university and many life science companies. In addition, it is important to further explore how to connect the testbed with other existing testbeds and networks such as the Applikationscenter in Mölndalen and the Swedish Arena for Additive Manufacturing of Metals.

Acknowledgements

The authors thank all companies and testbeds who participated and shared their knowledge. The authors thank Erik Asplund, Region Uppsala for his support and advice throughout the process. The authors also thank the reference group for their continuous feedback and support throughout the process. The reference group consisted of
Ulf Melin, VBN Components
Andreas Marcström, Cytiva
Jenny Nordqvist, UU Samverkan
Mikael Jonsson, UU

The study was funded by Region Uppsala, Uppsala universitet, and Vinnova through AM4Life.

References

[1] D. Khorsandi, A. Fahimipour, P. Abasian, S.S. Saber, M. Seyedi, S. Ghanavati, A. Ahmad, A.A. De Stephanis, F. Taghavinezhaddilami, A. Leonova, R. Mohammadinejad, M. Shabani, B. Mazzolai, V. Mattoli, F.R. Tay, P. Makvandi, 3D and 4D printing in dentistry and maxillofacial surgery: Printing techniques, materials, and applications, Acta Biomater. 122 (2021) 26–49.

[2] D. Ukobitz, Organizational adoption of 3D printing technology: a semisystematic literature review, J. Manuf. Technol. Manag. 32 (2021) 48–74. https://doi.org/10.1108/JMTM-03-2020-0087.

[3] O. Linde, J. Persson, Kartläggnings- och behovsinventering av test och demonstrationsinfrastruktur, 2015.

[4] Tillväxtanalys, Vilka faktorer påverkar uppbyggnaden av en testbädd? En analys av programmet Testbäddar inom miljöteknik, 2017.

[5] S. Valizadeh, L. Söderberg, Nulägesanalys av additiv tillverkning i Norra Mellansverige, Sandbacka Science Park, Sandviken, 2020.

[6] A. Strondl, H. Nilsson-Åhman, Omvärldsanalys på temat material och AM i Uppsala, 2019.

[7] A. Strondl, M. Uhlirsh, S. Karlsson, P. Hallberg, M. Widefelt, E. Hrhya, L. Nyborg, E. Lindgren, G. Lindwall, FuRam – Follow-up on research needs for industrialization of metal additive manufacturing, 2021.

[8] S. Laforet, Organizational innovation outcomes in SMEs: Effects of age, size, and sector, J. World Bus. 48 (2013) 490–502. https://doi.org/10.1016/J.JWB.2012.09.005.

[9] S.J. Schuldt, J.A. Jagoda, A.J. Hoisington, J.D. Delorit, A systematic review and analysis of the viability of 3D-printed construction in remote environments, Autom. Constr. 125 (2021).

[10] I.I. Andreadis, C.I. Gioumouxouzis, G.K. Eleftheriadis, D.G. Fatouros, The advent of a new era in digital healthcare: A role for 3D printing technologies in drug manufacturing?, Pharmaceutics. 14 (2022). https://doi.org/10.3390/PHARMACEUTICS14030609.

[11] J. Rybicka, A. Tiwari, G.A. Leeke, Technology readiness level assessment of composites recycling technologies, J. Clean. Prod. 112 (2016) 1001–1012. https://doi.org/10.1016/J.JCLEPRO.2015.08.104.

[12] J. Wang, Y. Zhang, N.H. Aghda, A.R. Pillai, R. Thakkar, A. Nokhodchi, M. Maniruzzaman, Emerging 3D printing technologies for drug delivery devices: Current status and future perspective, Adv. Drug Deliv. Rev. 174 (2021) 294–316. https://doi.org/10.1016/J.ADDR.2021.04.019.