Slutrapport for perioden: 1. marts 2016 til 31. december 2019

EUDP-sekretariatet, Energistyrelsen
Niels Bohrs Vej 8D
6700 Esbjerg
CVR-nr.: 59 77 87 14

Projektidentifikation

Ansøgningsår og runde (I eller II): 2015 II	
Titel: Additiv Produktion (3D print) af Store Strukturer indenfor Vindmølleindustrien	
Journal nr.: 64015-0580	
Tilsagnshaver (projektansvarlig virksomhed):	Vestas Wind Systems A/S
Projektleder: Lars Behrendt	
Virksomhed/institution: Vestas	**Telefon:** 60932265
Adresse: Hedeager 42, DK-8200, Aarhus	**E-mail:** labet@vestas.com
Projektdeltagere:	
Technical University of Denmark, DK	
Aarhus University, DK	
National Composites Centre, UK	
SP Group A/S, DK	
Projektets startdato: 01/03-2016	**Projektets slutdato:** 31/12-2019
Projektets totale varighed i mdr.: 46	
Antal mdr. tilbage af projektperioden: 0	

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Version History

V00 January 2020 First version just after project closure

V01 February 2020 Several updates, Sec 5.3 still missing

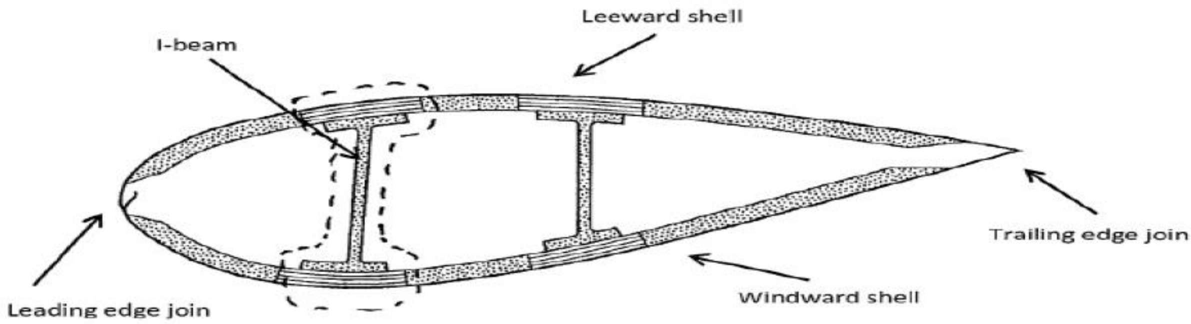
V02 March 2020 Final version for EUDP

V03 May 2021 Final version after financial audits

1. The purpose of the project

From the original EUDP application:

> The present pilot project will develop and demonstrate an extrusion-based AM set up that can produce a large dynamically loaded composite structure (8 m long I-beam) from a wind turbine blade, while obtaining the required strength, stiffness, surface smoothness, and durability.



I-beam in a wind turbine blade

The scope of the project was to develop and demonstrate the methods, processes and tools needed to support industrial scale additive manufacturing of structural elements printed in polyurethane reinforced with long carbon fibre tows. Such structural elements could be commercially used in e.g. wind turbine blades.

2. Summary

The project was kicked-off in the start of 2016.

It was from the start clear to – and accepted by - all the participants and the EUDP that the project scope was very ambitious, and that the risk of not meeting all project objectives was high.

Following the original planning, all activities were to be completed by the end of 2018. However, a slow resource ramp-up, and due to the technical complexity, it had in early 2018 become obvious, that this schedule could not be met. Consequently, the project applied to the EDUP for an 18-month extension leading to a project closure in the middle of 2020, and this within the original monetary budget. EUDP approved this.

An important element of the project scope was understanding and controlling the properties of the polyurethane. This was the responsibility of AU. The characteristics of the unhardened and later hardened polyurethane depends a lot on the mix of the two main components, as well as on various additives and catalysts. AU has conducted several series of experiments focused on describing and controlling the polyurethane during mixture, fibre wetting, printing and hardening. The idea was from the start to be able to regulate the material characteristics while printing in order to optimize the printing process and the end object, and the results from AU indicated that this would be possible.

A central part of the project was developing the print head. This was initially the task of DTU, but the ownership of this task was in 2018 moved to NCC, with DTU in a supporting role. At NCC a first desktop version of the print head was built in 2018 printing with only one fibre tow. This was a good start for functional tests. Several experiments were conducted with several layers of fibre printed on different surfaces. The experiments, though still far from being close to industrial scale application, proved that it was possible to obtain a repeatable quality, measured as fibre volume percentage, of the printed objects.

Vestas and SP together conducted several experimental tests focused on demonstrating that industrial scale applicability could be achieved. By industrial scale is meant printing at a deposition rate of around 200 kg/hour with 32 5k carbon tows. The tests concluded that fibre wetting at this speed could be done with the right design of the print head, and that – with some additional investments – industrial scape application of the method would be within reach.

Two problem never resolved in the project was printing concave surfaces and printing only with fibre placement (extrusion) as opposed to pultrusion. This lead in 2019 to the conclusion that the originally planned end demonstration could not be done. An application for a reduced end demonstration, to be performed in 2020, was subsequently submitted to EUDP.

EUDP did not approve the reduced scope for the end demonstration, and therefore the project steering group decided to close the project by the end of 2019.

3. Dansk sammenfatning

Projektet blev startet i begyndelsen af 2016.

Det var fra starten klart for – og accepteret af – alle deltagere og EUDP, at projektets indhold var meget ambitiøst, og at risikoen for ikke at nå alle projektets mål var høj.

Ifølge den oprindelige planlægning skulle alle aktiviteter have været afsluttet ved udgangen af 2018. Som følge af en forsinket ressourceallokering, og den tekniske kompleksitet, var det i begyndelsen af 2018 blevet klart, at denne tidsplan ikke kunne overholdes. Som en konsekvens af dette ansøgte projektet EUDP om en 18-måneders forlængelse, der betød projektafslutning i midten af 2020, og dette indenfor det oprindelige økonomiske budget. EUDP godkendte dette.

En vigtig del af projektets indhold var at opbygge forståelse for og kontrol af polyurethanens egenskaber. Dette var AUs ansvar. Karakteristikken af den ikke-hærdede, og senere hærdede polyurethan afhænger i høj grad af sammensætningen af de to komponenter, såvel som af forskellige tilsætningsmidler og katalysatorer. AU har gennemført adskillige serier af eksperimenter fokuseret på at beskrive og kontrollere polyurethanen under blanding, fibervædning, printning/udlægning og hærdning. Det var fra starten tanken, at man skulle kunne regulere materialeegenskaberne under printning for at kunne optimere print-processen og slutproduktet, og resultaterne fra AU indikerede, at dette ville være muligt.

En central del af projektet var at udvikle printhovedet. Dette var oprindeligt DTUs opgave; men ejerskabet af denne opgave blev i 2018 flyttet til NCC, stadig med DTUs understøtning. Hos NCC blev en første lille version af printhovedet, der printede et enkelt fiberbundt, bygget i 2018. Det var en god start på de funktionelle test. Adskillige eksperimenter blev gennemført med flere lag af fibre udlagt på forskellige overflader. Eksperimenterne beviste, selv om de stadig var langt fra industriel anvendelse, at det var muligt at opnå en forudsigelig kvalitet i form af volumenprocent af fibre i det printede objekt.

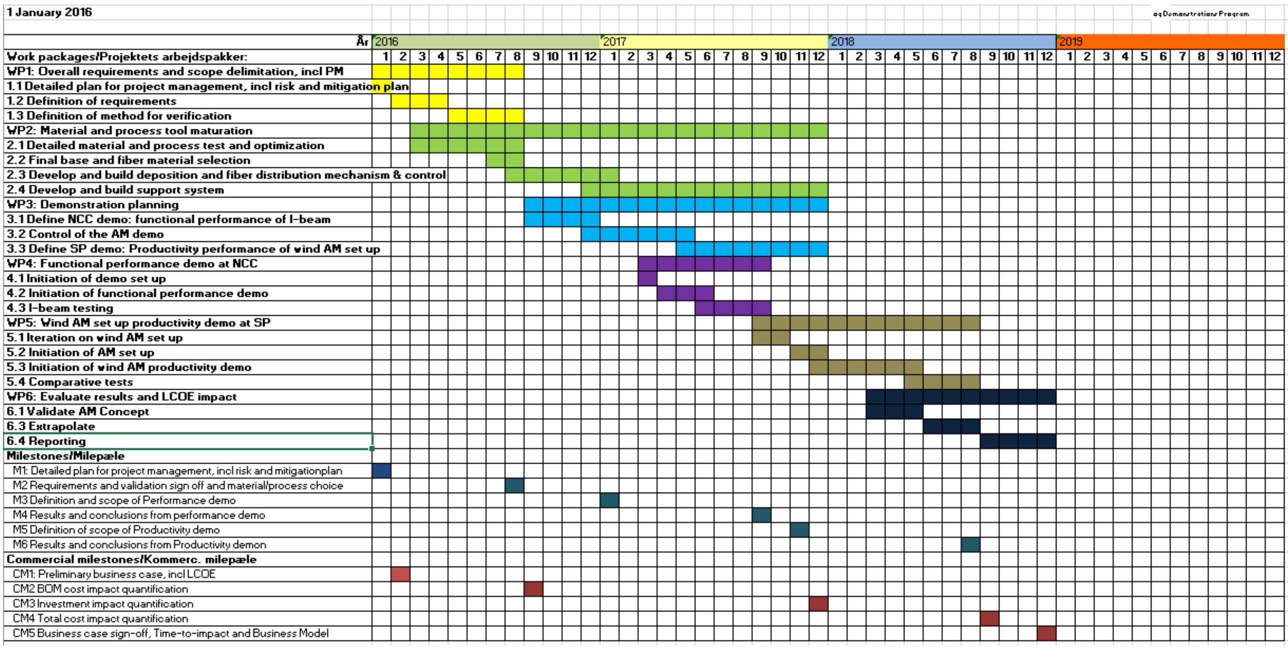
Vestas og SP gennemførte sammen flere eksperimentelle tests fokuseret på at demonstrere, at industriel skala anvendelighed kunne opnås. Ved industriel skala forstås printning ved en udlægningshastighed på omkring 200 kg/time med 32 5k karbon fiberbundter. Testene viste, at vædning af fiberbundterne ved denne hastighed kunne gøres med det rigtige design af printhovedet, og at – med nogen yderligere investeringer – industriel skala anvendelse af metoden ville være indenfor rækkevidde.

To udfordringer, der blev aldrig overvundet i projektet, var printning/udlægning på konkave overflader og printning alene ved fiberudlægning (extrusion) i modsætning til at trække fibrene ud gennem printhovedet. Dette ledte i 2019 til konklusionen om, at den oprindeligt planlagte slutdemonstration ikke kunne gennemføres. En ansøgning om en reduceret slutdemonstration, der skulle gennemføres i 2020, blev derefter indsendt til EUDP.

EUPD godkendte ikke den reducerede slutdemonstration, og derfor besluttede projektets styregruppe at lukke projektet ved udgangen af 2019.

4. Project execution

4.1. Original plan



4.2. Major changes

Relative to the original project plan the following major changes have incurred during the execution of the project:

- During 2016 the project suffered some initial delays caused by the late allocation of the relevant staffing from the universities. EUDP was informed about these delays in the 2017 yearly report, but as the project still had a hope of recovering the delays, a formal application for approval of a new schedule was submitted to EUDP.

- In the start of 2018, the Steering Group decided to move the development of the print head from DTU to NCC. An updated detailed planning further revealed that the project could not complete in 2019. A new schedule moved the completion date to the middle of 2020 while staying within the original overall budget. Both changes were approved by EUDP.

- During the late 2018 and the start of 2019 it became evident that the final demonstration as planned in the original EUDP application could not be done. Therefore, in June the project applied EUDP for reducing the scope of this demonstration. Late October 2019 EUDP responded that this application was not approved.

This list does not include minor changes like e.g. moving hours between different categories of employees inside the budget of individual project participants. Several such changes have taken place, all of which have been approved by EUDP.

4.3. Decision to close the project

Due to the decision of EUDP not to approve the June 2019 application for a changed scope for the final demonstration, the Steering Group of the project decided to terminate the project by the end of 2019.

5. Project economy

5.1. Original budget

Version: EUDP 1.12

Vælg version: EUDP — Select language: Dansk

Projektnummer

Projekt titel: Additive manufacturing of large structures in the wind industry

Projektleder: Thomas Christensen
E-mail: thomc@vestas.com
Telefon: 25148386

	Projektansvarlig	Partner 2	Partner 3	Partner 4	Partner 5	Partner 6	Partner 7
Virksomhed	Vestas	DTU	SP Group	AU	NCC-Bristol University		
SE nummer	10403782	30060946	15701315	31119103	RC000648		
Virksomhedstype (vælg)	Privat virk. eller GTS	Universitet	Privat virk. eller GTS	Universitet	Universitet	Privat virk. eller GTS	Privat virk. eller GTS
Aktivitetstype (vælg)	Eksperimentielt udviklingssamarbejde	Eksperimentielt udviklingssamarbejde	Eksperimentielt udviklingssamarbejde	Eksperimentielt udviklingssamarbejde	Industriel forskningssamarbejde	Industriel forskningssamarbejde	Industriel forskningssamarbejde
Antal ansatte	20.000	5.721	1.136	8.217	175		
Årlig omsætning /mio. kr.	51.825,0	4.678,8	1.102,1	6.146,7	129.820.000,0		
Aktiver (mio kr.)	52.477,0	7.945,1	884,7	3.063,1	6.086.520,0		
Virksomhedsstørrelse, EU	Stor virksomhed	Stor virksomhed	Stor virksomhed	Stor virksomhed	Stor virksomhed	Småvirksomhed	Småvirksomhed
Forskningsandel (%)	0%	0%	0%	0%	0%	0%	0%
Vejlende maks støtteprocent	40%	90%	40%	90%	90%	0%	0%

Samlet økonomi

	Budget	Regnskab	Budget	Regnskab	Budget	Regnskab	Budget	Regnskab	Budget	Regnskab	Budget	Regnskab	Budget	Regnskab	Budget	Regnskab
Funktionær timer	34.862	#VALUE!	7.000	#VALUE!	7.500	#VALUE!	2.490	#VALUE!	7.875	#VALUE!	9.997	#VALUE!		#VALUE!		#VALUE!
Teknisk/adm timer	11.970	#VALUE!	4.980	#VALUE!	3.000	#VALUE!	2.490	#VALUE!	1.500	#VALUE!	0	#VALUE!		#VALUE!		#VALUE!
Personaleudgifter																
Funktionær løn	15.161.200	#VALUE!	3.682.000	#VALUE!	2.821.517	#VALUE!	1.309.740	#VALUE!	3.006.061	#VALUE!	4.341.882	#VALUE!		#VALUE!		#VALUE!
Teknisk/adm løn	3.611.816	#VALUE!	1.568.700	#VALUE!	821.500	#VALUE!	784.350	#VALUE!	437.266	#VALUE!		#VALUE!		#VALUE!		#VALUE!
Overhead procent	*46%*	*#VALUE!*	*50%*		*44%*		*50%*		*44%*		*44%*					
Overheadomkostninger	8.700.814	#VALUE!	2.625.350	#VALUE!	1.602.927	#VALUE!	1.047.045	#VALUE!	1.515.064	#VALUE!	1.910.428	#VALUE!	0	#VALUE!	0	#VALUE!
Lønomkostninger total	27.473.830	#VALUE!	7.876.050	#VALUE!	5.245.944	#VALUE!	3.141.135	#VALUE!	4.958.391	#VALUE!	6.252.310	#VALUE!	0	#VALUE!	0	#VALUE!
Andre omkostninger																
Instrumenter og udstyr	1.774.985	#VALUE!		#VALUE!	500.000	#VALUE!		#VALUE!	500.000	#VALUE!	774.985	#VALUE!		#VALUE!		#VALUE!
Bygninger	156.000	#VALUE!		#VALUE!		#VALUE!	156.000	#VALUE!		#VALUE!		#VALUE!		#VALUE!		#VALUE!
Andre driftsudgifter, herunder materialer	2.203.000	#VALUE!	500.000	#VALUE!	500.000	#VALUE!	500.000	#VALUE!	500.000	#VALUE!	203.000	#VALUE!		#VALUE!		#VALUE!
Eksterne leverancer / underleverancer	10.000.000	#VALUE!	10.000.000	#VALUE!		#VALUE!		#VALUE!		#VALUE!		#VALUE!		#VALUE!		#VALUE!
Indtægter (negative tal)	0	#VALUE!		#VALUE!		#VALUE!		#VALUE!		#VALUE!		#VALUE!		#VALUE!		#VALUE!
Andet, herunder rejser og formidling	1.107.500	#VALUE!	200.000	#VALUE!	200.000	#VALUE!	100.000	#VALUE!	100.000	#VALUE!	507.500	#VALUE!		#VALUE!		#VALUE!
Overhead procent	*11%*	*#VALUE!*			*44%*				*44%*		*44%*					
Overheadomkostninger	1.665.613	#VALUE!	0	#VALUE!	528.000	#VALUE!	0	#VALUE!	484.000	#VALUE!	653.613	#VALUE!	0	#VALUE!	0	#VALUE!
Andre omkostninger total	16.907.099	#VALUE!	10.700.000	#VALUE!	1.728.000	#VALUE!	756.000	#VALUE!	1.584.000	#VALUE!	2.139.098	#VALUE!	0	#VALUE!	0	#VALUE!
Sum	**44.380.929**	**#VALUE!**	**18.576.050**	**#VALUE!**	**6.973.944**	**#VALUE!**	**3.897.135**	**#VALUE!**	**6.542.391**	**#VALUE!**	**8.391.408**	**#VALUE!**	**0**	**#VALUE!**	**0**	**#VALUE!**

Finansiering

Støtteprocent	*50%*	*#VALUE!*	7%	#VALUE!	90%	#VALUE!	35%	#VALUE!	90%	#VALUE!	90%	#VALUE!		#VALUE!		#VALUE!
Støtte total 50%	**22.381.290**	**#VALUE!**	**1.300.324**	**#VALUE!**	**6.276.550**	**#VALUE!**	**1.363.997**	**#VALUE!**	**5.888.152**	**#VALUE!**	**7.552.268**	**#VALUE!**	**0**	**#VALUE!**	**0**	**#VALUE!**
Anden finansiering 0%	**0**	**#VALUE!**		**#VALUE!**		**#VALUE!**		**#VALUE!**		**#VALUE!**		**#VALUE!**		**#VALUE!**		**#VALUE!**
Egenfinansiering 50%	**21.999.639**	**#VALUE!**	**17.275.727**	**#VALUE!**	**697.394**	**#VALUE!**	**2.533.138**	**#VALUE!**	**654.239**	**#VALUE!**	**839.141**	**#VALUE!**	**0**	**#VALUE!**	**0**	**#VALUE!**

Nøgletal

Partner andel			41,9%	#VALUE!	15,7%	#VALUE!	8,8%	#VALUE!	14,7%	#VALUE!	18,9%	#VALUE!	0,0%	#VALUE!	0,0%	#VALUE!
Funktionær kr/time	435	#VALUE!	526	#VALUE!	376	#VALUE!	526	#VALUE!	382	#VALUE!	434	#VALUE!	0	#VALUE!	0	#VALUE!
TAP kr/time	302	#VALUE!	315	#VALUE!	274	#VALUE!	315	#VALUE!	292	#VALUE!	0	#VALUE!	0	#VALUE!	0	#VALUE!
Andre omkostninger %	38,1%	#VALUE!	57,6%	#VALUE!	24,8%	#VALUE!	19,4%	#VALUE!	24,2%	#VALUE!	25,5%	#VALUE!	0,0%	#VALUE!	0,0%	#VALUE!
Støtte per time	296	#VALUE!	46	#VALUE!	450	#VALUE!	221	#VALUE!	476	#VALUE!	563	#VALUE!	-	#VALUE!	-	#VALUE!

Kommentarer

The 10 mill DKK in external services is expenses for the additive manufacturing set up in the SP location.

Anvisningsoplysninger

Pengeinstitut:	Nordea
Reg. nr. :	2149
Konto	651117097

Underskrift

5.2. Major changes

The project has, as described in section 4.2, experienced several changes. Despite these, the revised budgets have always stayed within the limits of the original budget.

5.3. Balance at closure

Version: EUDP 1.12 | Vælg version: EUDP | Select language: Dansk

Projektnummer: 64015-0580

Projekt titel: Additive manufacturing of large structures in the wind industry

Projektleder: Lars Behrendt
E-mail: LABET@vestas.com
Telefon: 60932265

	Projektansvarlig	Partner 2	Partner 3	Partner 4	Partner 5	Partner 6	Partner 7
Virksomhed	Vestas	DTU	SP Group	AU	NCC-Bristol University		
SE nummer	10403782	30060946	15701315	31119103	RC000648		
Virksomhedstype (vælg)	Privat virk. eller GTS	Universitet	Privat virk. eller GTS	Universitet	Universitet	Privat virk. eller GTS	Privat virk. eller GTS
Aktivitetstype (vælg)	Eksperimentielt udviklingssamarbejde	Eksperimentielt udviklingssamarbejde	Eksperimentielt udviklingssamarbejde	Eksperimentielt udviklingssamarbejde	Industriel forskningssamarbejde	Industriel forskningssamarbejde	Industriel forskningssamarbejde
Antal ansatte	20.000	5.721	1.136	8.217	175		
Årlig omsætning /mio. kr.	51.825,0	4.678,8	1.102,1	6.146,7	129.820.000,0		
Aktiver (mio kr.)	52.477,0	7.945,1	884,7	3.063,1	6.086.520,0		
Virksomhedsstørrelse, EU	Stor virksomhed	Stor virksomhed	Stor virksomhed	Stor virksomhed	Stor virksomhed	Småvirksomhed	Småvirksomhed
Forskningsandel (%)	0%	0%	0%	0%	0%	0%	0%
Vejlende maks støtteprocent	40%	90%	40%	90%	90%	0%	0%

Samlet økonomi

	Total Budget	Total Regnskab	Projektansvarlig Budget	Projektansvarlig Regnskab	Partner 2 Budget	Partner 2 Regnskab	Partner 3 Budget	Partner 3 Regnskab	Partner 4 Budget	Partner 4 Regnskab	Partner 5 Budget	Partner 5 Regnskab	Partner 6 Budget	Partner 6 Regnskab	Partner 7 Budget	Partner 7 Regnskab
Funktionær timer	37.463	34.624	9.395	9.704	7.071	6.898	2.490	710	6.560	7.046	11.947	10.267		-		-
Teknisk/adm timer	6.785	3.896	980	-	500	1.335	2.490	121	2.815	2.440	0	-		-		-
Personaleudgifter																
Funktionær løn	16.578.299	14.200.586	4.941.770	4.834.585	2.658.696	2.531.370	1.309.740	399.605	2.479.756	2.573.703	5.188.337	3.861.323		-		-
Teknisk/adm løn	2.193.621	1.259.878	308.700	-	137.000	418.712	784.350	25.773	963.571	815.393		-		-		-
Overhead procent	*46%*	*46%*	*50%*		*44%*		*50%*		*44%*		*44%*					
Overheadomkostninger	8.700.318	7.118.202	2.625.235	2.417.293	1.230.106	1.298.036	1.047.045	212.689	1.515.064	1.491.202	2.282.868	1.698.982	0	-	0	-
Lønomkostninger total	27.472.239	22.578.667	7.875.705	7.251.878	4.025.802	4.248.119	3.141.135	638.066	4.958.391	4.880.298	7.471.205	5.560.305	0	0	0	0
Andre omkostninger																
Instrumenter og udstyr	1.774.985	1.405.257		-	500.000	394.862		-	500.000	407.550	774.985	602.845		-		-
Bygninger	156.000	9.597		-		-	156.000	9.597		-		-		-		-
Andre driftsudgifter, herunder materialer	2.203.000	1.096.870	500.000	62.356	500.000	505.283	500.000	29.407	500.000	351.864	203.000	147.960		-		-
Eksterne leverancer / underleverancer	10.000.000	0	10.000.000	-		-		-		-		-		-		-
Indtægter (negative tal)	0	26.358		-		26.358		-		-		-		-		-
Andet, herunder rejser og formidling	1.107.500	566.647	200.000	-	200.000	145.846	100.000	85.793	100.000	76.747	507.500	258.261		-		-
Overhead procent	*11%*	*41%*			*44%*				*44%*		*44%*					
Overheadomkostninger	1.665.613	1.283.734	0	-	528.000	471.834	0	-	484.000	367.911	653.613	443.989	0	-	0	-
Andre omkostninger total	16.907.099	4.388.463	10.700.000	62.356	1.728.000	1.544.183	756.000	124.796	1.584.000	1.204.072	2.139.098	1.453.055	0	0	0	0
Sum	**44.379.337**	**26.967.130**	**18.575.705**	**7.314.234**	**5.753.802**	**5.792.302**	**3.897.135**	**762.863**	**6.542.391**	**6.084.370**	**9.610.304**	**7.013.360**	**0**	**0**	**0**	**0**

Finansiering

	Total Budget	Total Regnskab	Projektansvarlig Budget	Projektansvarlig Regnskab	Partner 2 Budget	Partner 2 Regnskab	Partner 3 Budget	Partner 3 Regnskab	Partner 4 Budget	Partner 4 Regnskab	Partner 5 Budget	Partner 5 Regnskab	Partner 6 Budget	Partner 6 Regnskab	Partner 7 Budget	Partner 7 Regnskab
Støtteprocent	*50%*	*64%*	7%	7%	90%	84%	35%	33%	90%	89%	90%	90%		0%		0%
Støtte total 50%	22.380.144	17.362.316	1.300.299	511.996	5.178.422	4.893.639	1.363.997	253.276	5.888.152	5.391.381	8.649.273	6.312.024	0	-	0	-
Anden finansiering 0%	0	0		-		-		-		-		-		-		-
Egenfinansiering 50%	21.999.193	9.604.813	17.275.406	6.802.238	575.380	898.663	2.533.138	509.587	654.239	692.989	961.030	701.336	0	-	0	-

Nøgletal

	Total Budget	Total Regnskab	Projektansvarlig Budget	Projektansvarlig Regnskab	Partner 2 Budget	Partner 2 Regnskab	Partner 3 Budget	Partner 3 Regnskab	Partner 4 Budget	Partner 4 Regnskab	Partner 5 Budget	Partner 5 Regnskab	Partner 6 Budget	Partner 6 Regnskab	Partner 7 Budget	Partner 7 Regnskab
Partner andel			41,9%	27,1%	13,0%	21,5%	8,8%	2,8%	14,7%	22,6%	21,7%	26,0%	0,0%	0,0%	0,0%	0,0%
Funktionær kr/time	443	410	526	498	376	367	526	563	378	365	434	376	0	0	0	0
TAP kr/time	323	323	315	0	274	314	315	213	342	334	0	0	0	0	0	0
Andre omkostninger %	38,1%	16,3%	57,6%	0,9%	30,0%	26,7%	19,4%	16,4%	24,2%	19,8%	22,3%	20,7%	0,0%	0,0%	0,0%	0,0%
Støtte per time	313	377	53	52	479	436	221	255	476	456	563	487	-	-	-	-

Kommentarer

Projektet er 12-15 måneder bagud relative til den plan, der var en del af den oprindelige EUDP ansøgning.

Som tidligere rapporteret skyldes forsinkelsen dels, at det tog længere tid end forventet af få projektteamet etableret, og dels, at de tekniske udfordringer har vist sig større end oprindeligt antaget.

Anvisningsoplysninger

Pengeinstitut:	Nordea
Reg. nr. :	2149
Konto	651117097

Underskrift: 6/5 2021

EUDP ELFORSK FORSK EL FORSK VE

Classification: Restricted

6. Main technical results

Several material systems have been characterized and printing parameters have been obtained for three of them. In order to achieve this equipment was developed alongside with analytical methods for material characterization and quality control.

It has been concluded, that applying a carefully calibrated use of the right mix of polyol, isocyanate and catalyst combined with a correct material handling, maybe including cooling or heating, it will be possible during the additive manufacturing process to control important parameters such as viscosity, curing time and gel-temperature. This can enable the detailed design of a system where the chemical characteristics are modified ‘on the fly’ during manufacturing, in order to ensure an outcome with the desired product characteristics.

For the carbon fibre tows, it has been demonstrated that the full wetting with resin can be achieved in a controlled manner, while the fibre is being pulled through the end effector (the print head). Many experiments have been made with placing the fibre on various surfaces, mostly by pressing the wetted fibre towards the surface with a wheel-mechanism.

When using the uncured two-component chemicals, clogging of the end effector and any other mechanism getting into contact with the wetted fibre tows has been a concern. Clogging can be delayed but hardly completely avoided, and therefore a future industrial application should be built such that the parts subject to clogging are cheap and easily replaceable.

Other learnings cover the mechanisms needed for feeding the end effector with the fibre tows, and for cutting the fibres. As the final, large demonstration did not take place, these mechanisms were never brought to a higher maturity.

In the majority of experiments the fibre tows have, in layers on top of each other, been stretched out on a receiving surface, and in most cases compacted by a wheel mechanism. With the wet fibres, this will not work on concave surfaces, and the project was not able to provide a solution for that problem.

It has been demonstrated that a repeatable quality, in terms of fibre volume and matrix quality, of the final, hardened and fibre reinforced polyurethane can be achieved. The quality achieved indicate that, with some further development, the quality will be good enough for industrial application.

Several experiments have indicated, that scaling up the work done in this project to an industrial application level, measured as high deposition rate and controllable quality, will be possible with some further investment.

7. Commercial applicability

The business opportunity pursued in the original scope of this project was based on a scenario of on-site AM of smaller wind turbine blades, using a portable and automated AM set-up and sliding support as substitution for the current expensive moulds. This is still relevant but not possible to pursue until the AM is more mature than it has been possible to achieve in this project.

With the results obtained in this project, one commercial applicability is to speed up the build time needed for new wind turbine blade moulds. To achieve this some additional investments will be needed, and Vestas is considering performing this as an in-house development project.

8. Appendix 1: Vestas/SP technical reporting

8.1. Summary

The project has from the point of view of Vestas and SP provided new knowledge in several areas:

- Increased understanding of polyurethane and the possibilities of using this material in combination with continuous fibre tows
- Knowledge of the mechanics of fibre wetting and possibility of obtaining industrial material deposition rates
- A better understanding of the overall complexity of designing a setup where thermoset chemicals are combined with continuous fibre tows

The main Vestas and SP activities have been centred around a series of experimental tests. Different method with different experimental designs of the print head, including fibre tow tensioner and cutting mechanism, were applied with focus on achieving the industrial performance of the solution.

Eventually, the tests concluded that only pultrusion of the fibres seemed doable at industrial scale. This conclusion was one of the main motivations behind the decision in 2019 to apply for a changed scope for the final demonstration.

It is recognised that several problems have remained unsolved despite the efforts of the combined project team:

- How to print wet fibres without tension (extrusion)
- How to print thin layers of fibre without post-compression
- Printing concave surfaces
- Printing at industrial scale at high deposition rate with an acceptable and predictable quality

8.2. Main achievements

The original planning called for:

- Vestas taking care of project management and coordination of the technical activities
- SP providing technical expertise and hosting the setup of the final demonstration

The main project activities will in the following be described in chronological order, with the perspective of Vestas and SP.

In 2016 the project was kicked off at a meeting in the months of May.

During the rest of the year most activities were centred around getting the project started, establishing the needed meeting structures and a detailed planning including drafting a set of top-level requirements.

Further, SP made some first investigations into the final demonstration with respect to what was needed to establish the needed test bench, where and how it could be acquired, and with which lead times. Also, the option of re-building some old Vestas owned machines from the blade factory in Lem was considered. Due to technical constraints, however, this option was de-selected.

The first chemical samples of polyurethane were through SP obtained from the supplier Covestro and distributed to DTU and AU.

In 2017 the Vestas and SP continued with the planning of the setup for the final demonstration. This included investigating using an existing machine available through SP. This option was abandoned as SP decided to use the machine in their running production.

On the Vestas side, another project was re-building a CNC machine located in Lem to do some AM related experiments. At a point, it was considered also to use this machine in the present project, but that did not happen as the project re-building the CNC machine was stopped by Vestas.

In 2018 Vestas and SP performed a detailed planning of the final demonstration. The original plan called for building a dedicated machine for this and operating it at the facilities of SP in Skjern. SP made the needed space available in one of their facilities and started the HSE planning and the process for getting permission from the municipality for using the relevant chemicals.

The detailed planning involved a detailed design and subsequent costing by machine suppliers often used by Vestas. Unfortunately, it turned out that just building and commissioning the machine for the final demonstration would cost approximately 8MDKK of the 10MDKK for doing the final demonstration. At that point if was still not proven that the printing process could be sufficiently matured to perform the planned final demonstration. Further, the cost of the setup needed would not leave enough money for performing the final demonstration.

After some discussions among the project participants, it was subsequently decided to move the final demonstration away from SP and into NCC in the UK. NCC had a three-robot facility that would be upgraded with new robots and control system in 2019, and the project could rent access to this facility for a four months period during the final demonstration. This would enable the project to stay within the overall project budget.

Further, during 2018 a series of tests was performed at an improvised test rig at SPs facility in Skjern. Various print-heads aimed at demonstrating fibre wetting at high printing speed was designed and physically produced by Vestas, and these were used in the trials in Skjern. It was successfully demonstrated that the carbon tows could be wetted at higher printing speeds, and the results also indicated that the from an industrial point of view needed deposition rates probably could be obtained if the concept was future matured.

In 2019 – starting late 2018 – it became increasingly clear that the technical achievements and the foreseen maturity of the technical solution did not support the final demonstration as originally planned. The original planning called for printing an I-beam, i.e. a structure including concave surfaces. It was not possible to keep the printed carbon tows in position in that case. The alternative of printing a conical spar was considered instead, but that would just have been wrapping a two-dimensional surface around a pre-shaped mould, just adding complexity without adding real value to the demonstration.

Therefore, the project steering group decided to apply to EUDP for a scope change whereby the final demonstration would produce a flat plate printed in polyurethane with long tows of fibre. The application for that change was sent in to EUDP on June 19, 2019. On October 25, 2019 EUDP formally replied that the application for the change could not be approved. Subsequently, the project steering group decided to terminate the project by end of December 2019.

9. Appendix 2: DTU technical reporting

9.1. Summary

DTU Mekanik har gennem projektet formået at få etableret et laboratorie for bredformats 3D print. Laboratoriet huser 2 bredformats-3D printere med tilhørende værktøjssystemer; en 5-akset parallel-kinematisk 3D printer der muliggør konturering ved brug af et tiltende værktøjshoved samt en rotationsprinter der kan fremstille dorne over hvilke vædede kulfibertov and pultruderes. De to maskiner har et arbejdsområde på 1.5x1.5x2 meter og der er på anlæggene fremstillet en prototype vinge til en vindturbine i kulfiberforstærket hærdeplast.

Det etablerede know-how og den etablerede laboratoriefacilitet er blevet et stærkt aktiv i DTU Mekaniks forsknings- og undervisningsfaciliteter og vil være et vedblivende element af DTU Mekaniks infrastruktur.

Der er etableret unik viden omhandlende kompleksiteten af håndtering af kontinuere kulfibre i en hærdeplast matrix. Her specielt vedrørende de værktøjer der skal udvikles for at håndtere udlægning af vædede fibre i acceptabel kvalitet. Denne viden vil fremadrettet blive udbygget således at det etablerede laboratorie kan benyttes som teknologidemonstrator for netop bredformats-3d print af kompositmaterialer.

10. Appendix 3: AU technical reporting

10.1. Summary

Several material systems have been characterized and printing parameters have been obtained for three of them. In order to achieve this equipment was developed alongside with analytical methods for material characterization and quality control.

10.2. Main achievements

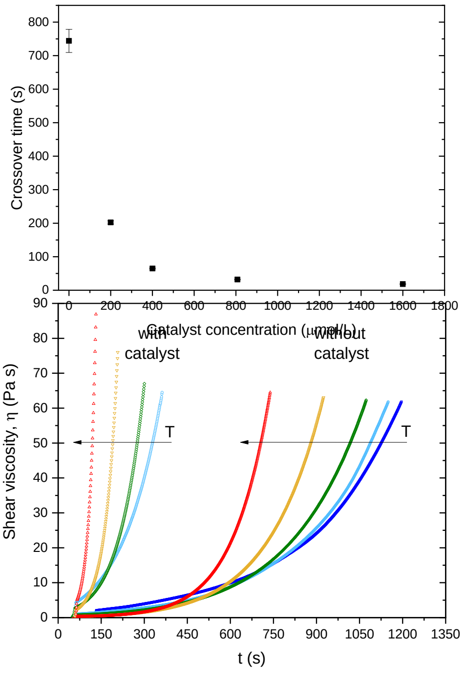
Instruments

To print larger specimens, an extension of the AUP3Steel 3D printer [1] in the x-direction and assembled a wider 3D printer with a building surface of 220×220×620 mm^3 [2]. To dispense and dose chemicals, two pumping systems was designed and developed. For larger volumes (10L+) a valve less rotating and reciprocating piston metering pumps was designed and controlled by a 3-axis stepper motor driver. This included mechanical installation of the three pumps, design and manufacturing of electronics, programming of both electronics and a windows-based control program. For smaller volumes, syringe pumps were designed [3] and integrated into the 3D printer electronics and firmware. Six standalone programs were made for printer control (two), G-code generation (three) and metering/calibration (one). Some (five) necessary additions was realized during experimental work which resulted in design and manufacturing of mechanics, electronics, and programming of chemical pre cooling [4], moist control, mixing conditioning, temperature monitoring, etc. These was built as standalone and later integrated in the system (with more or less ease).

Catalyst and material characterization

Due to the toxicological profile and expected future ban of tin catalysts it was chosen not to apply this catalyst. Instead tertiary amines and bismuth carboxylate catalysts was employed as substitutes and the latter showed a satisfactory range of reaction times (from sec to hr.) and was therefore chosen as the main catalyst. Several, two component thermosets, resin systems (two experimental and two commercial systems) have been evaluated in order to identify the optimal formulation for 3D printing of the polyurethane (PUR).

Determination of gel point, of two experimental formulations, was achieved with three different approaches: rheometer, nail [5], and hand mixing measurements (see image). Because the reaction between polyol and isocyanate is highly exothermic (T raised up to 110 °C) and the rheometer measurements are performed at controlled temperatures, a higher crossover time was observed with the rheometer measurements compared to nail and hand mixing. Therefore, during the 3D printing tests (determine the best time window for the deposition of PUR layers) it was realized that thermal control of chemicals and during mixing was necessary. The analysis was performed on three PUR systems (n=100+). In general, for each formulation, an increase in catalyst concentration lowered the time to reach the gel point (see image). Polymerization time was systematically controlled between 1 minute to 30 minutes with ease.

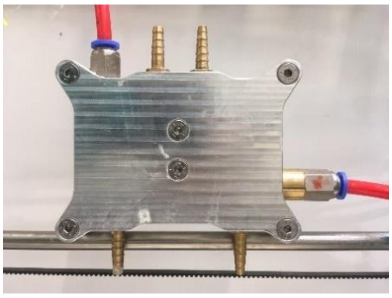
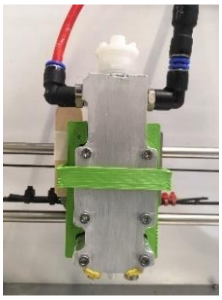
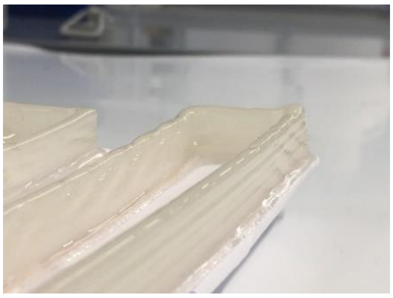


The viscosity as a function of catalyst concentration and temperature (see image) for two experimental formulations was examined (n = 100+) and control over the curing time was demonstrated for the tested parameters. Viscosity profiles determined at different catalyst and temperature values (n=200+) were used to define the specifications of the 2K pilot facility and final machine.

Thermal characterization (mainly DSC measurements) were carried out on experimental formulations and the heat enthalpy of 191 ± 7 J/g regardless of catalyst concentration (n=50+). The transition glass temperature was found to be 80 ± 7 °C regardless of catalyst concentration (n=50+). Moreover, DSC studies were made (n=20+) to determine the acceptable off-mix ratio of polyol and isocyanate that will allow to minimized properties variations in the final product. The determined off-mix ratio 98-102 % was further used to describe the specifications of the 2K machine. Heat capacity of the cured experimental formulation was determined to 1.26 ± 0.12 J/K g (n=20+), while activation energy decreased between 13 to 30 % upon addition of the catalyst (n=50+).

3D Printing of PUR

3D Printing of PUR turned out to be challenging especially when catalyst was added to the polyol. The main problem was clogging of the static mixer used to mix the two chemicals. A pre cooling system was developed for chemical cooling and a cooling system for the static mixer (see images). Printing tests and temperature profiling was performed (n=150+) in order to optimize layer-to-layer adhesion and structural stability.

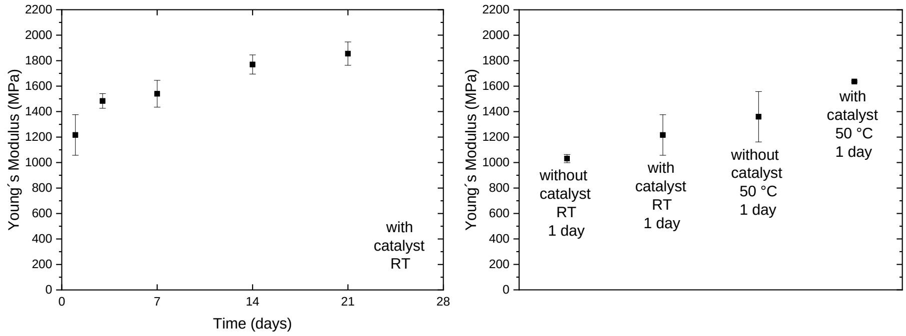




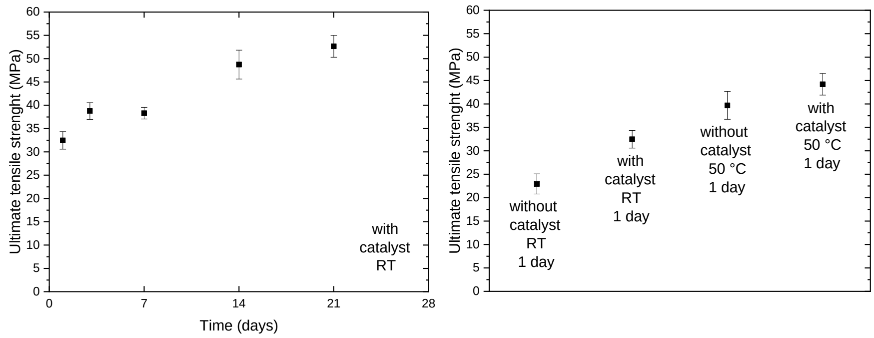
Cure shrinkage

An experimental setup was developed, (mechanic, electronic and programs) to determine the shrinkage of the experimental PUR during cure. The change in volume of the material was measured as a function of catalyst concentration (n=20+). For both resin systems, the measured shrinkage increased as a function of catalyst concentration, up to a maximum of 4% for the highest catalyst concentration tested.

Tensile test

To determine ultimate tensile strength (UTS) and Young's modulus (E) of the material as a function of catalyst concentration, post-curing time and temperature (n=450+). The results indicate that E and UTS increase over time, approaching a plateau after 21 days at room temperature. Similar E and UTS were obtained by post curing the PUR for 1 day at 50 °C (see images).





Fiber-PUR characterization

A method combining TGA and density measurements was implemented in order to determine void, fiber, PUR volume and weight fractions in carbon fibers-PUR composites made during printing (n=15). This was applied as a quality control of the 3D printed fiber reinforced PUR composites.

References

[1] Original AUP3Steel 3D printer (https://www.thingiverse.com/thing:1579315) and assembly instructions (http://www.prusa.samle.dk/page-4/)

[2] AUP3Steel Wide (https://www.thingiverse.com/thing:1689048) 3D printer.

[3] Technical drawings and assembly guide for syringe pumps (https://osf.io/qcnjt/).

[4] 3D Printing of Two-Component Thermoset - Temperature Control of Reactants, Nina F. Mortensen, Bachelor thesis, 2016.

[5] Catalytic influence on gel point and exothermic behavior in solid Polyurethane 3D print, Esben. S. Madsen, bachelor thesis, 2017.

11. Appendix 4: NCC technical reporting

11.1.Summary

11.1.1.Early scope

- Consultation to project team for composite manufacturing guidance
- Development of a capability to simulate the deposition of fibre and cure kinetics of the resin
- Introduction to automated layup technologies course given to consortium November 2017

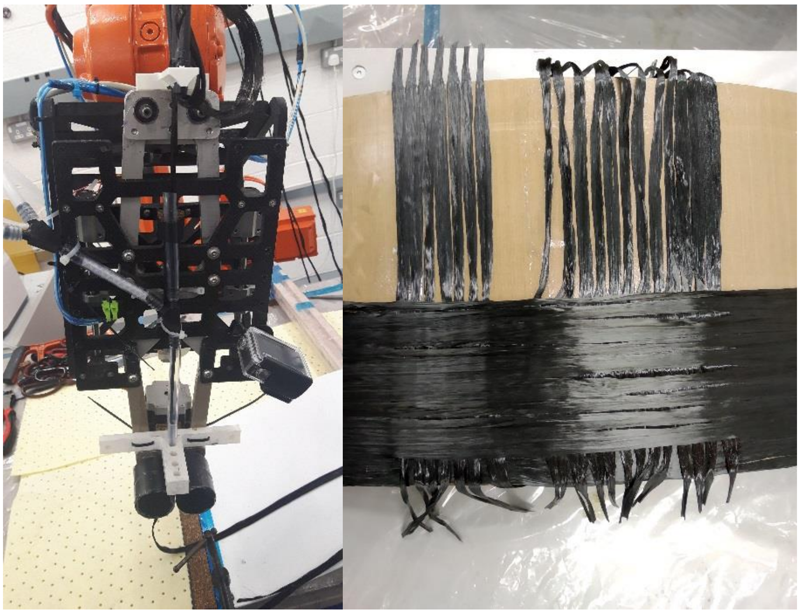
11.1.2.Modified project scope (2018)

- Engagement with R&D supply chain to purchase developmental platform for small-scale printing of composites (Orbital EE1) (EE = End Effector, the print head)
- With EE1, begin developing our understanding of the process, manufacturing samples of increasing complexity
- Analysis of existing samples for reference quality
- Thorough quantitative coupon testing to compare process parameters
- ACM4 presentation in Montreal [1]
- Combined lessons learned and other NCC knowledge to design and build (with Vestas), a modular workbench platform
- Using this workbench platform to drive design selection of EE2
- Preformed a range of testing to evaluate the process parameters for EE2
- EE2 design – mechanical and control
- Auxiliary sub-system design and/or specification for outsource
    - Creel
    - Routing
    - 2K machine (2K machine = machine handling the two component chemicals)
- Tool design for final demonstrator layup

11.2.Main achievements

11.2.1.Development of End Effector 1

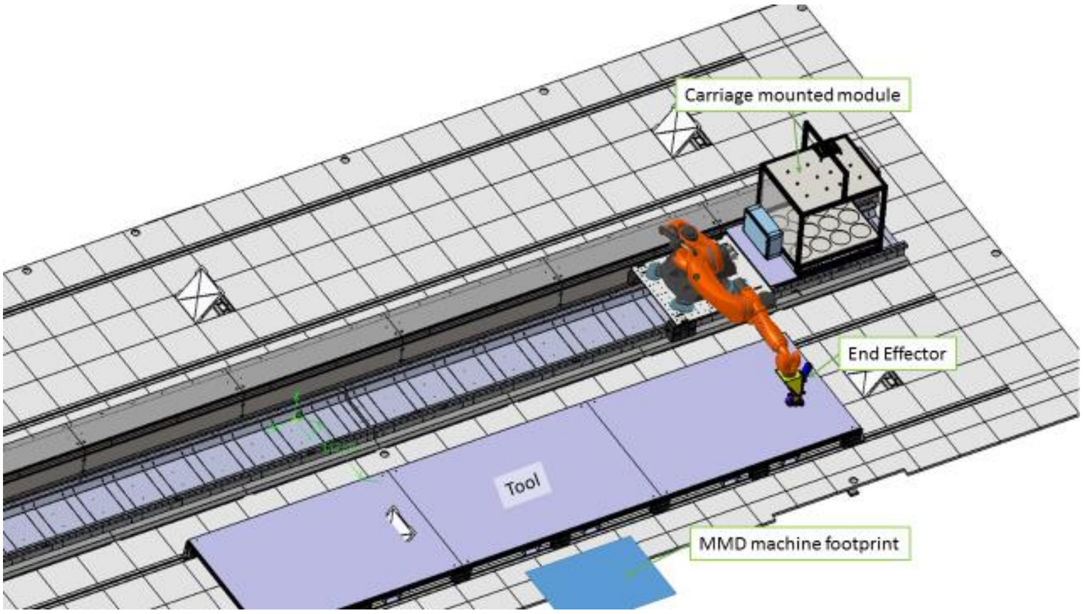
The NCC specified the End Effector 1 development platform and placed an order with Orbital Composites for the initial build. NCC then spent six months refining the design through a rigorous testing schedule to arrive at an end effector capable of continuous additive manufacture. Review of the design lead to the development of a specification for the next generation end effector and system.

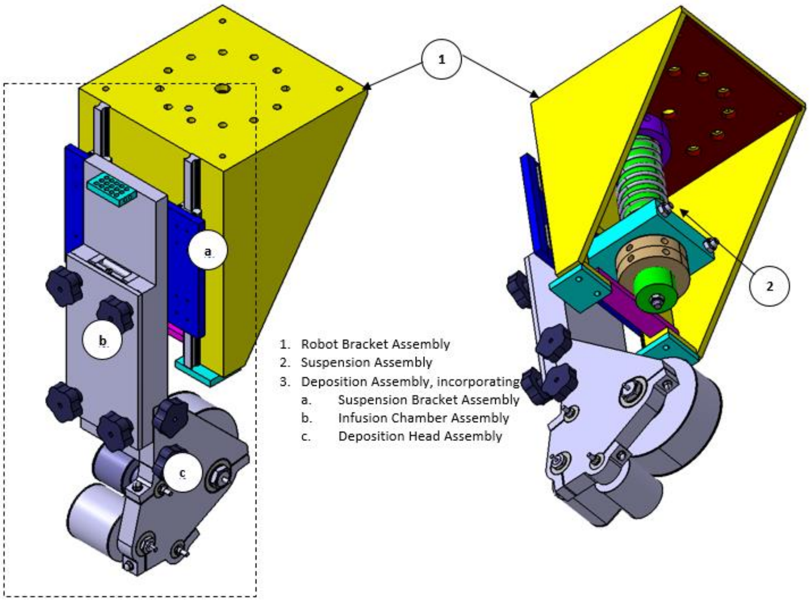


- Development work on EE1 platform to improve wet out & feed systems
- Results of testing presented at ACM4 in Montreal
- Printing of small-scale components, including double-curvature structure
- Microscopy of existing samples, and comparison with coupons made using EE1
- Lessons learned used to generate EE2 specification

11.2.2.Development of End Effector 2

The NCC continued development for End Effector 2 on a modular workbench platform, testing and refining concepts. At project closure, NCC had completed the design work on EE2 to proposal design review level: the design concepts are all completed for a system that is capable of continuous additive manufacture of carbon fibre composite at 50kg/hr.





- Thorough understanding of:
  - Resin delivery,
  - Tow delivery
  - Infusion module
  - Tension take off module
  - Cutting module
  - Compaction module

- A design concept for a system capable of continuous additive manufacture at 50kg per hour
- Detailed technical specification for the design concept,
- Risk register of detailing where risks remain in implementation
- Specification for a 2K machine capable of supplying the resin with the correct degree of control
- Supply chain mapping for 2K machine

References

[1] Druiff, P., Di Francesco, M., Dell'Anno, G., Ward, C. Wet Fibre Placement Process Optimisation, 4th International Symposium on Automated Composites Manufacturing, Montreal 25th-26th April 2019. (https://www.concordia.ca/content/dam/ginacody/research/concom/docs/4th-symposium-Program.pdfhttps://www.concordia.ca/content/dam/ginacody/research/concom/docs/4th-symposium-Program.pdfhttps://www.concordia.ca/content/dam/ginacody/research/concom/docs/4th-symposium-Program.pdf page 61)