Institution: University of Wales Trinity Saint David		
Unit of Assessment: 32		
Title of case study: Utilisation of advanced design and manufacturing technologies for the 3D production of patient-specific surgical systems in the veterinary domain.		
Period when the underpinning research was undertaken: 2016-2019		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Dr Ffion O'Malley Dr Huw Millward Lloyd Stoker Prof Alan Lewis	Medical Project Engineer Research Director Technical Director Professor of Design & Innovation	Jan 2015 - Nov 2019 Oct 2016 - Sept 2019 Aug 2014 - Present Nov 2014 – May 2018 Jan 2019 – Oct 2020
Period when the claimed impact occurred: 2016-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

This case study describes impacts of commercially applied design research in the veterinary domain by employing computer-aided design (CAD), non-destructive testing (NDT) and additive manufacturing (AM) technologies at the Wales Centre for Batch Manufacture (CBM). The research involved **a)** the design and development of bespoke surgical devices for the efficient treatment of osteosarcoma (bone cancer) in large breed dogs across the UK, and **b)** the creation of bespoke orthopaedic implants for small dogs. The main impacts arising from the research are the development and surgical adoption of a virtual surgery planning system in a 3D design space, and in the design optimisation of two types of surgical device: custom implants and cutting guides. The implant assembly is designed and 3D printed as a single consolidated geometry using advanced AM technologies, such as electron beam melting (EBM). The design and production of 3D contoured custom implants and cutting guides match exactly to the individual patient's anatomy that facilitates surgical accuracy (such as tumour resection) and the overall success of the surgical procedure. Both procedures are now recognised in surgical practice, achieve enhanced surgical outcomes and reduce the surgical time by up to 50%. CBM's services are accredited ISO13485:2016 for the Design & Manufacture of Custom Made 3D printed surgical guides and implants intended for end user sterilization.

2. Underpinning research

Research has been carried out by a medical engineering team at UWTSD's Wales Centre for Batch Manufacture (CBM) in collaboration with British veterinary specialists (Langford Vets, Moorview Vets and Willows Veterinary Centre and Referral Service). Initial design research starting from 2016 was conducted as increasing numbers of dogs with congenital spinal malformations were being presented at veterinary referral centres, such as kyphosis which is usually caused by wedge-shaped vertebrae in the mid thoracic region. Medical design engineers at CBM worked in collaboration with two veterinary neurologists/neurosurgeons Tom Shaw and Tom Harcourt-Brown (Langford Veterinary Hospital) to develop a new surgical technique using additive manufacturing (AM) technologies. Example 2 (part 4) for instance, shows the anatomical spine model of a 1-year old pug with a presenting complaint of a kypgotic spinal malformation and associated T3-L3 myelopathy. The consultant surgeon specified that the case required the developed stackable system of a surgical drilling guide and spinal stabilisation implant. Using virtual planning computer-aided design (CAD) platforms **[i, ii]**, the trajectory angles of each screw were placed with the consultant surgeon to allow for the sufficient bone purchase and avoiding any critical anatomical landmarks in the dorsal spinal processes and the chosen vertebras of interest. A surgical drilling guide was additively manufactured in a medical grade biocompatible polymer. Five bicortical pedicle screws and five dorsal screws in the dorsal spinal processes were attached through the 3D printed titanium stabilisation implant to the spine. This and similar research cases contributed to CBM's accreditation in 2018 for ISO13485: 2016 (design & manufacture of custom made 3D printed surgical guides and implants intended for end user sterilization).

Virtual limb sparing 3D planning system
Following the success and adoption of this procedure, further research aimed to overcome the limitations of the conventional surgical implant systems for the efficient treatment of osteosarcoma (bone cancer) in dogs. According to veterinary surgeon Jonathan Deacon at Moorview Vets Ltd, the traditional surgical technique for treating osteosarcoma had three main limitations, **a**) the unplanned resection of tumour and implantation of multiple plates increases crucial surgical time; **b**) solid structures of the implants not only make them heavy but also prevent further bone regeneration; **c)** traditional implant systems frequently require manual adjustments (contouring plates to match the bone geometry) that lead to poor surgical outcomes such as inadequate fit and imprecise restoration of anatomical axes of affected limbs. The research commenced from the development of a new CAD methodology. The main aim was to develop a virtual 3D planning system and a set patient-specific surgical tools to overcome the identified limitations when using traditional limb sparing implants. The research therefore involved the development of the following new surgical tools: **a)** patient-specific cutting guides for the precise resection of the affected bone segment by tumour (Fig. 1, 2); **b**) a light-weight 3D contoured and optimised implant with the incorporated 3D lattice structure that replaces the removed portion of the bone (tumour) and propagates bony ingrowth (Fig 3). The research involved multiple interactive CAD design screen share sessions with veterinary specialists at Moorview Vets, Ltd and AM fabrication of various design concepts followed by clinical experiments on cadaver dogs. The finalised virtual limb sparing 3D planning system comprises the following steps:

- **DICOM data segmentation.** During the segmentation step, captured computed-tomography (CT) scan data are processed in a specialised medical software and an accurate 3D model representation of the affected bone is extracted.
- **CAD planning.** The second step involves CAD design of patient-specific 3D cutting guides and 3D contoured plate with the incorporated 3D mesh structure. The developed virtual planning technique commences from the 3D placement of cutting planes on the extracted bone data. Positioned planes are then employed for the design of personalised cutting guides that specify bone cutting directions and the region of interest (ROI). When the cutting guides are designed, the osteosarcoma segment of the bone (ROI) is virtually removed. The removed cavity is then employed for the design of 3D mesh structure that stimulates the bone ingrowth when a custom limb-sparing device is additively fabricated. A custom-shaped 3D implant is designed to secure two fragments of the affected bone. The designed implant is virtually attached to the limb with cortical and bicortical orthopaedic screws. 3D screw trajectories are carefully planned to achieve the most secure bone purchase. The developed CAD procedure has been adapted for the efficient virtual planning of the angular limb deformity correction in dogs **[i]** (Figures 1, 2,3 and Example 1).
- **Non-destructive testing.** The designed CAD geometry of the 3D implant is analysed using computational methods, such as Finite Element Analysis (FEA). Since the implant is load-bearing, the aim of the FEA analysis is to mitigate the risks via incorporation of several patient specific scenarios. This involves multiple simulations that are conducted to analyse stress & strain values generated from different gait(s) such as walking, trotting, running etc. These simulations are a combination of both static and dynamic analysis that enable in identifying any immediate risk to the implant **[ii]** (Figure 4).
- **3D Additive Manufacturing (3D AM) step.** Modelled and analysed in FEA 3D CAD data of the virtually planned patient-specific limb-sparing system are then analysed (post-processed) with the specialised industry-leading 3D slicing software Materialise Magics (Materialise NV, Belgium). The 3D slicing software is required for the subsequent layered 3D Additive manufacture step using certified biocompatible materials. 3D CAD data of the anatomical models and personalised cutting guides are fabricated using the Stereolithography manufacturing method (SLA 5000, 3D systems Inc.) using a biocompatible (ISO10993, USP Class VI for short-term contact with organs and blood tissue) UV-light curable resin (Watershed XC11122). 3D modelled CAD data of the custom plate with incorporated lattice structures are fabricated on Electron Beam Melting (EBM) Arcam Q10 system using a medical grade alloy Ti6Al4V ELI (implantable devices for long term use) **[ii].**

3. References to the research

i. Gupta, A, Millward, H. O.Malley, F, Lewis A. (2019) Probabilistic Finite Element Analysis of Bespoke Titanium Veterinary Implants; II International Conference on Simulation for Additive Manufacturing, SIM-AM, Pavia, Italy, 11th-13th September 2019. Proceedings. ISBN: 978-84-949194-8-0

ii. Carwardine, D. Gosling, M. Burton, N. O'Malley, F. Parsons, K., Three-Dimensional-Printed Patient-Specific Osteotomy Guides, Repositioning Guides and Titanium Plates for Acute Correction of Antebrachial Limb Deformities in Dogs. *Veterinary and Comparative Orthopaedics and Traumatology* 34 (01). Published online 30/04/20

Invited Presentation

iii. O'Malley, F. Stoker, L. Using additive manufacturing to create bespoke orthopaedic implants for the veterinary market. CBM Formnext Presentation. 14th November 2018

Accreditation

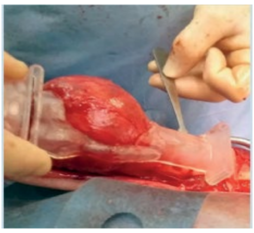
iv. **ISO13485:2016** for the Design & Manufacture of Custom Made 3D printed surgical guides and implants intended for end user sterilization

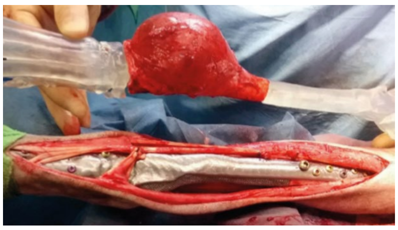
v. **ISO 9001:2015** for the provision of a design, prototyping and small batch manufacturing.

4. Details of the impact

Virtual limb-sparing 3D planning technique for the treatment of Osteosarcoma

Osteosarcoma is the most common type of bone cancer in dogs, treatable either by amputation or limb-sparing surgery. Limb-sparing surgeries, also known as limb-saving or limb-salvage techniques, are performed to give veterinary patients an alternative to amputation. During limb-sparing surgeries the tumorous section of the bone is removed and replaced with either a prosthesis, allograft bone, or allograft-prosthetic combination. The prosthesis is fixed to the remaining bones with screws and bone cement or the bone grows into the prosthesis. Commercial "off-the-shelf" limb-sparing systems require manual adjustments (contouring plates to the bone geometry) that lead to poor outcomes, prolonged surgery time, inadequate fit and restoration of anatomical axes. In collaboration with British veterinary specialists at Moorview Vets Ltd, CBM has developed a virtual limb-sparing 3D planning technique to overcome the limitations caused by the use of mass produced devices. The developed 3D virtual planning technique has currently been successfully applied for 14 surgical cases for the efficient treatment of osteosarcoma in dogs across the UK, and surgeons continue to employ the system in very complex cases where traditional solutions are not applicable.





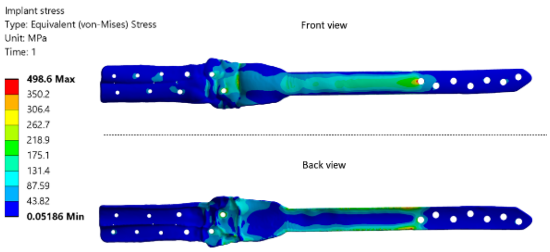


Figure 1 (left to right). The developed patient-specific cutting guides and surgical implant **[ii]**
Figure 2. Surgical Implant, Mesh lowered into removed defect area & Anatomical Model with Tumour Defect
Figure 3. 3D printed surgical models used for demonstration of virtually planned procedures.
Figure 4. Finite Element Analysis results **[i]**

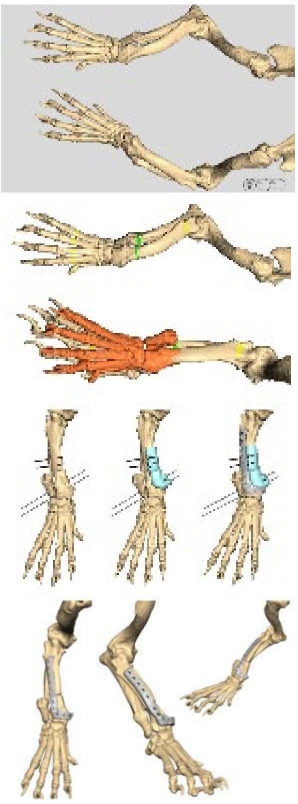
Clinical outcomes

The surgical procedure adopted by Moorview Vets continues to grow in adoption within the UK veterinary community with successful cases undertaken by Langford Veterinary Services, Rutland House Referrals, K2 Veterinary Referral Ltd and Vet 3D. With further adoption and cost reduction the techniques have the potential to become the mainstream procedure. The carefully planned 3D patient-specific cutting guides and implants reported above now make it possible to reduce surgery time by up to 50%, improve accuracy and mitigate risks of implant failure by virtually testing the device before the additive manufacture (AM) step. This can be followed by the implantation of customised implants, which include a metal mesh spacer attached to the remaining bone. The developed virtual surgical technique is particularly good option for large and giant breed dogs where amputation may not be well tolerated. As demonstrated in Figure 3, 3D printed anatomical models are precise three-dimensional replicas that provide an invaluable aid of visualising the region of interest at the time of surgery or when planning or discussing treatment options. Anatomical 3D printed models also provide information to surgeons regarding implant components and instrumentation to be used.

Key benefits in this regard are: i) accuracy of tumour resection; ii) reduced surgical time; iii) reduced tissue trauma, iii), improved strength of fixation, and iv) improved bone regeneration. The accuracy of the tumour resection and the reduction in surgical time are particularly important as conventional limb spare surgeries carry very high infection rates, these being directly correlated to surgical time and also to some degree the trauma caused by the surgeon during the procedure. In this regard, the trauma is reduced (although not eliminated) but the use of the cutting guides and by the use of custom implants as both reduce the amount of dissection and tissue retraction during the surgery. A second key benefit is that conventional implants are not ideal for limb sparing surgeries. Firstly, because different screw sizes in the radius and metacarpals are usually needed, secondly because the lengths of the solid central section and the sections with holes varies case to case, and thirdly because screws in two metacarpals is usually optimal. While surgeons report that it can be done with normal plates, this is not without compromises (e.g. pre-drilled holes are of the wrong size and in sub-optimal positions) and the bespoke guides and implant offer improved strength of fixation in this regard. Finally, the use of additive manufacturing to produce the mesh cylinder (lattice structure) promotes better surgical outcome with regard to improved bone regeneration. Traditional limb-spare techniques use either a metal spacer in the excised radius, just left a gap, put in a cortical allograph, or tried to regenerate bone with distraction osteogenesis. None of these methods are consistently successful in achieving the aim of load-sharing with the implant. Grafting the bone inside the additive manufacturing mesh by comparison is capable of regenerating bone along the whole deficit and produces the best available clinical outcomes.

Bespoke orthopaedic implants for small dogs.
CBM researchers have also worked in close collaboration with two British vets, Dr Kevin Parsons an orthopaedic vet based at the small animal hospital at Langford Vets, in Bristol, and a former colleague Tom Shaw a neurosurgeon, now at Willows Veterinary Centre and Referral Service in Solihull. The collaboration has developed new surgical procedures employing these virtual planning, non-destructive testing and additive manufacturing techniques to create bespoke orthopaedic implants for small dogs. Certain breeds of small dog are genetically prone to developing potentially life changing conditions. In dachshunds and Shih Tzu's for example, abnormal bone growth can sometimes cause their front paws to point outwards. Pugs and other breeds with corkscrew tails are susceptible to spinal problems caused by misshapen bones. Fortunately, if diagnosed in time, these conditions can be treated with surgery. However, the size and weight of the patients can often present a challenge to veterinarian surgeons. With such small animals, corrective surgery to drill and cut bones, stabilize vertebrae or reposition limbs is a laborious and intricate process, with little or no margin for error.

In this regard, since 2016, Parsons and Shaw have been using custom additive manufactured anatomical guides, surgical guides and titanium implants in daily practice with animals referred to them suffering from angular limb deformity or spinal malformation. In doing so, they have not only been able to improve surgical accuracy and the predictability of outcomes, but also reduce theatre time. Integral to Langford Vets' additive journey has been its partnership with CBM, who oversee the production of bespoke surgical guides (either in polymer or metal) and titanium implants to match exactly to each individual patient's anatomy to restore mechanical and/or aesthetical functions. Each implant design, follows precise specifications from the Langford Vets' surgical team, using CT or MRI diagnostic imaging data, and is manufactured on a GE Additive Arcam EBM Q10plus on site at CBM's facility in South Wales. This is now an established surgical procedure. Routinely employed applications are detailed in examples 1 and 2.

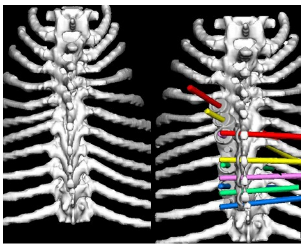


Example 1. Diagnosis: Lucca (Shih Tzu) at aged one was diagnosed by Dr Kevin Parsons with angular limb deformity. CBM was briefed by Parsons to design and additively manufacture a cutting and repositioning surgical guide required to reposition and straighten the limb and a titanium implant to hold the limb in its new repositioned location.

Repositioning: the desired result was for the angular limb to be repositioned to mimic the opposite side limb. The lower limb was to be repositioned into its preferred location and screw trajectories were planned to hold the correction implant in place.

Surgical Guides: two cutting planes were used achieve the correct planned repositioned angle of the limb. Four K wires were placed in the limb to be used alongside the two surgical guides to re-orientate the lower limb. The bone bound surface of this surgical guides contoured the anatomy so that it located and fit accurately onto the bone. The four K-wires were used alongside the Repositioning Guide to orientate the lower limb into its correct planned position. The bone bound surface of this surgical guide contoured the anatomy so that it located and fit accurately onto the bone.

Implant.10 screw holes were designed onto the implant to attach it to the limb. The bone bound surface of this Titanium implant contoured the anatomy so that it located and fit accurately onto the bone.

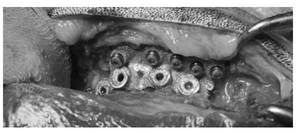


Example 2. Diagnosis: Topsey (Pug), at aged one, was diagnosed by Tom Shaw with hind limb weakness caused by a severe spinal malformation. CBM were briefed to produce a stabilisation implant required to work in conjunction with a surgical drilling guide.

Surgical Guide: Five drill cylinders were used to guide the pilot drill to achieve the correct trajectories. The bone bound surface of this surgical guide contoured the spinal anatomy so that it located and fit accurately onto the bone.

Implant. Ten screw holes were designed onto the implant and located in the same position as the drill cylinders to achieve the correct trajectories. The bone bound surface of this Titanium implant contoured the spinal anatomy so that it located and fit accurately onto the bone.

Surgical outcome: The surgeons now employ this procedure for complex malformations of the spine. They have also starting to use this system as part of surgical treatment for subarachnoid diverticulae, to cover the laminectomy defect and stabilise the adjacent vertebrae. This is to reduce the incidence of adhesions between the cord and surrounding scar tissue, which in canine patients seems to be a the most common reason for recurrence of clinical signs, and to reduce instability to try and prevent cyst reformation.



5. Sources to corroborate the impact

1) Moorview Vets, Ltd.
2) Langford Small Animal Referral Hospital.
3) Willows Veterinary Centre and Referral Service.
4) Vet3D.
5) Applying Use of 3D Printing for Appendicular Surgery. *Veterinary Times* (April 1st 2019).
6) Using additive manufacturing to create bespoke orthopaedic implants for the veterinary market. Formax / GE Additive trade presentation. 14th November 2018
7) Testimonials