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# Why switch operations to digital manufacturing?

## *Presenting Jan Akmal's Doctoral Thesis with honorary award from STO Thesis competition*

Additive manufacturing, colloquially known as 3D printing, is rapidly emerging into a digital general-purpose technology akin to electricity, dynamos, and computers that are serving as not only the mainstay of our industries but are also shaping our ways of living. The current advent and proliferation of digital manufacturing technologies demand sustainable innovation of new practices, designs, and supply of products. Contributing to the emerging stream of research on advanced manufacturing technologies, Dr. Jan S. Akmal seeks to discover ways in which companies can benefit from switching operations between 1. part-specific conventional manufacturing that favors economies of scale and 2. general-purpose additive manufacturing that challenges the paradigm of economies of scale by economies of customization and personalization. Dr. Akmal addresses this feat through the following questions.

**How can companies profit from part-specific switchover between multiple additive manufacturing and static conventional manufacturing supplies?**

Together with practitioners of a case company in the mining and processing industry, Dr. Akmal proposes a novel digital operational practice — dynamic supplier selection — using a novel build-to-model mode of manufacturing (Table 1) for the provision of problematic spare parts.

From the economies of scale perspective, problematic parts were characterized as bespoke parts with intermittent demand, low volumes, high specificity, and high value. Typically, companies are familiar with such parts as they roughly follow the 20:80 pareto rule, with a limited number of parts generating the bulk of increasing costs owing to increasing minimum order quantities, inventory costs, and long lead-times.

Based on a field experiment, Dr. Akmal re-engineered 36 problematic parts, including individual parts, sub-assemblies, and tools (i.e. molds) for switching operations to additive manufacturing from conventional manufacturing to improve the spare parts service for end customers. Using the build-to-model mode, 3D models of the prospective parts were electronically transferred to seven additive manufacturing suppliers globally for dynamic retrieval of cost and lead-time data for each specific part. Design propositions are made for both static and dynamic batch sizes corresponding to typical customer orders of the case company. Readership is directed to Publication 1 for a detailed description of the operational dynamic supplier selection practice.

Empirical evidence from the multi-methods approach combining design science, scenario development, and case study confirmed that additive manufacturing can radically shift the performance frontier for problematic parts in conventional supply. The successful outcome prompted the case company to begin the introduction of dynamic operations. Figure 1 shows the problem embedded within the CIMO framework.

The generative mechanism of successful outcome is triggered by the encapsulation of design and additive manufacturing process instructions, exhibiting a thin boundary between each other. This drastically decreases mundane transaction costs due to the ease of transferring standardization, counting, and compensation across the boundary of the company.

| Concept | Description |
|---|---|
| Build-to-model | A mode of manufacturing that uses 3D model data to offer a direct response to demand using general-purpose technologies encompassing minimal transaction costs, i.e., asset specificity, uncertainty, and governance structures. |
| Dynamic supplier selection | An operational practice that allows the ability to choose an optimal supplier or suppliers by alternating between multiple suppliers for the procurement of individual parts without invoking significant transaction costs, i.e., asset specificity, uncertainty, and governance structures. |

*Table 1. Definitions of key concepts.*

In particular, the encapsulation reduces mundane transaction costs associated with e.g., co-ordination (contracting and negotiating product specifications), operations risk (information asymmetry), opportunism risk (loss of asset-specific resource control), and asset-specific reinvestments (tools, molds) for each idiosyncratic part. This enables highly interactive model-based supplier relationships for decentralized manufacturing which is governed through competition.

Transitioning from static to dynamic decision-making enables customers to engage with the e-commerce platforms or local sales teams of the companies to execute the final decision. This approach helps managers alternate between dynamic additive (multiple suppliers) and static conventional supply with respect to cost reduction, lead-time reduction, and supporting trade-offs in cost and lead-time in accordance with the customer requirements and value for each part.

Deploying dynamic supplier selection using build-to-model mode empowers companies to dynamically redefine the performance frontier and forge new customer relationships when procuring individual parts. Further, it facilitates a rapid assessment of the digital manufacturing potential within their part inventories.

Today, Finland fosters a growing value chain of digital manufacturing from design (e.g., Etteplan, Huld, Maker3D) to manufacturing (e.g., 3DFormtech, Delva, Materflow, 3DSTEP, Hetitec, Maker3D, Salon Metalelektro). Over the past decade or so, the number of digital manufacturing service providers has been growing globally, including in Finland. Even Finnish OEM companies (e.g., Wärtsilä and Valmet) have now internally initiated digital manufacturing operations.

Finnish service providers are pursuing ISO standardization —a few have already been certified— to ensure conformance. Though global service providers already have web-based automatic information tools, Finnish service providers should consider developing them as well in addition to the current email-based quotations.

Further, OEM companies would need to create information tools for automatic retrieval of data required for the dynamic supplier selection practice through the build-to-model mode. The long-term benefits of switching parts over to digital technologies should overtake the initial cost of preparing for a potential switchover. The switchover is a multidisciplinary process requiring skillsets of mechanical engineers, additive manufacturing experts, and operations managers. However, this should not deter companies because the prerequisites, once made ready, will remain so indefinitely to be pulled out from electronic inventories for different additive manufacturing technologies and suppliers with a dynamic response.

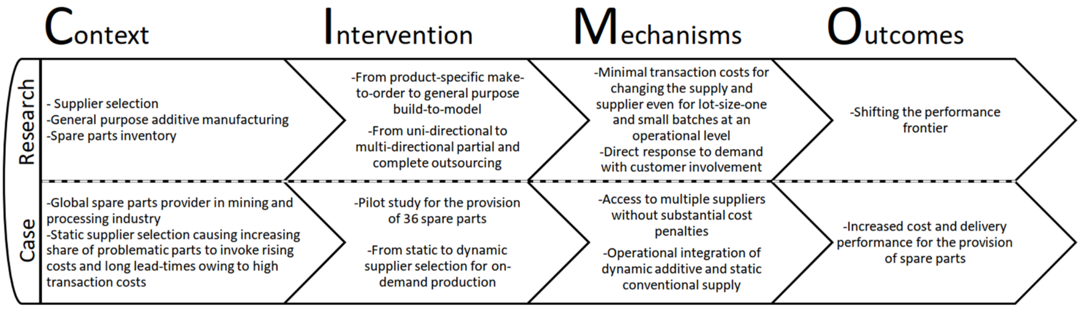


*Figure 1. Problem within the CIMO framework.*

**How accurately can you actually print the parts?**

Together with practitioners in the medical setting, Dr. Akmal develops a novel procedure to determine and evaluate the uncertainty and cumulative error in manufacturing an end-use implant (Figure 2).

Following preoperative planning for the reconstruction of craniomaxillofacial and joint systems, patient-specific implants are increasingly being created using additive manufacturing. The process involves medical imaging (3D scanning), segmentation (3D thresholding), digital design (3D modeling), and additive manufacturing (3D printing). The Food and Drugs Association (FDA) in the U.S. has already granted approval for over 225 medical implants.

First, the anatomical deformity and its functional counterpart are imaged using X-ray computed tomography (CT). Second, 3D block of voxels (cuboid structures) are segmented to obtain the target tissue (e.g. bone). Third, the implant is designed by mirroring the functional tissue to reconstruct the deformed counterpart. Finally, the 3D model of the implant is used for additive manufacturing.

Based on a descriptive case study and a laboratory experiment, Dr. Akmal proposes a safety margin that should be respected by surgeons to prevent ill-fitting implants and complications in surgical procedures.

Table 2 shows ways in which uncertainty and error budget increase as a function of each step of the process chain in creating a ready to use implant. Considering one measurement boundary condition, a worst-case cumulative error estimates to 1.7 mm (3.0 %) considering the maximum length (56.9 mm) of the implant. Likewise, for two measurement boundary conditions, it estimates to 2.3 mm (4.1 %). For example, if you have a hole in the skull for which you would need to fit an implant to, then the STL (3D model) error would be doubled for measuring the diameter of the implant. Segmentation error is the edge location error. Considering the start of the measurement (finding the zero location) and the end of the measurement (finding the final location) would increase the error by times 2.

Uncertainty from clinical imaging to the ready implant was 0.8 mm (1.4 %). Practitioners should also consider that the significant thresholding and additive manufacturing errors can be corrected to some extent through redesign of the implant. Readership is direct to Publication 2 for further details.

In Finland, companies, e.g. Planmeca and Electro Optical Systems Finland Oy, can offer such solutions for patient-specific implants on demand.

*Figure 2. The additively manufactured titanium implant with the supports (right) and without the supports (left).*

| Uncertainty and Error Budget of the End-Use Implant | | | | | |
|---|---|---|---|---|---|
| **Entity** | **Process** | **Error Source** | **Implant Error (L: 56.852 mm) [mm]** | **Non-Length Dependent Standard Uncertainty [mm]** | **Length Dependent Standard Uncertainty** |
| QA Phantom | CT Imaging: Multi-slice computed tomography | Volumetric | 0.191 | 0.0779 | 0.00117 |
| SD head | 3D Thresholding: Volume-based segmentation | DICOM to STL conversion (CT Protocol 1: 300 HU) | 0.602 | 0.602 | - |
| Implant | 3D Modeling: Digital design (Surface modeling) | CAD | 0.00005 | 0.0000029 | - |
| | 3D Printing / Additive manufacturing: Metal PBF | End-use implant | 0.914 | 0.0612 | 0.00866 |
| Cumulative | | | 1.71 | - | - |
| Cumulative involving two boundary surfaces | | | 2.31 | | |
| Combined standard uncertainty | | | | 0.610 | 0.0087 |
| Combined standard uncertainty (L: 56.852 mm) | | | | 0.787 mm | |

*Table 2. The cumulative inaccuracies of the additively manufactured end-use implant.*

**How can you additively manufacture smart parts?**

Together with practitioners in the medical field, Dr. Akmal develops and evaluates process interruption-based embedding focusing on an implant using four additive manufacturing methods, as shown in Figure 3.

One of the key elements that impact different treatment methods of human health is drug delivery to the target tissue. Following preoperative planning for the reconstruction of a mandible (lower jaw of human anatomy), Dr. Akmal seeks to equip the implant with drug delivery systems and radio frequency identification systems (RFID).

The process follows in a manner that cavities corresponding to the embedded elements are created inside the implant in a digital environment. Parametric models were created to embed ultra-high frequency (UHF) and high frequency (HF) RFID transponders inside the implant. Top two cavities, shown in green in Figure 3, represent UHF transponders, and the bottom two depict HF transponders. Eight conceptual channels were created for a potential drug release to the target tissue through diffusion.

Dr. Akmal also created a support feature, which terminated the fusion of materials to build supports inside the cavities for material extrusion and vat photopolymerization methods. The embedded cavities inside the mandible implant are shown in Figure 3. Readership is directed to Publication 3 for further details.

Figure 4 shows the outcome for each method. Embedding occurred by inserting a pause into the g-code of each additive manufacturing machine. All embedded transponders, fully enclosed within the implant, successfully communicated with an external transceiver to transfer patient-specific information that can include potential follow-ups. When equipped with internet of things (IoT), it can enable digital twins of the implant, which can allow for reproduction when needed.

The drug delivery channels were successfully manufactured for all four methods. When created with compatible biomaterials, the tailor-made channels can enable controlled drug release to the direct vicinity of need for bodily restoration.

This proof of concept opens a direction for embedding sensors inside the parts to produce infringement-proof smart parts that can facilitate big data retrieval, analysis such as machine learning, and evidence based decision-making such as replenishing parts when it reaches the end of its functional life cycle.

Recently, Dr. Akmal has also developed and evaluated self-sensing capabilities in additively manufactured parts by embedding conductive elements that are copper and continuous carbon fiber without process interruption. Dr. Akmal conducted electrical resistance measurements that showed a strong correlation with applied force and strain (Sensing tolerance<±2.6 %, R2>93.8 %, p-value < 0.005). Readership should follow Publication 4 for additional insights. ⬢

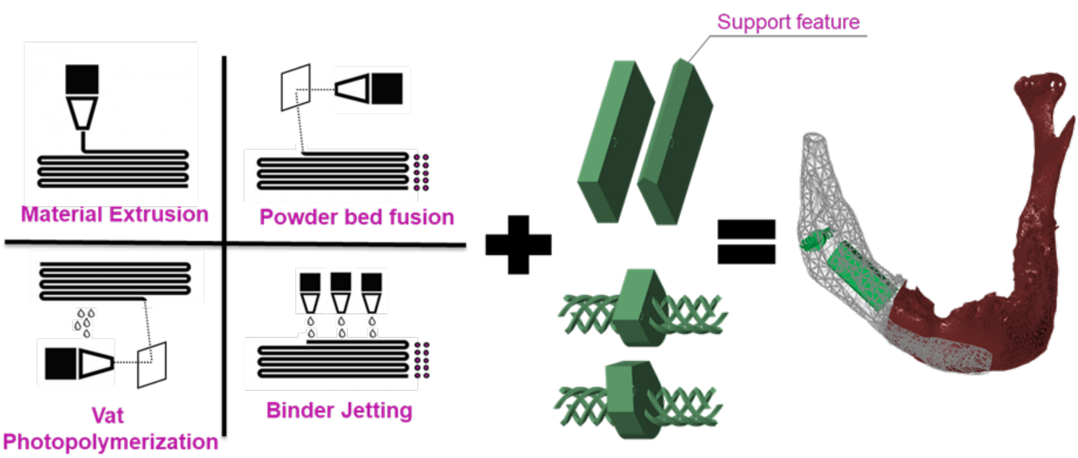


*Figure 3. Process interruption-based embedding using four additive manufacturing methods.*

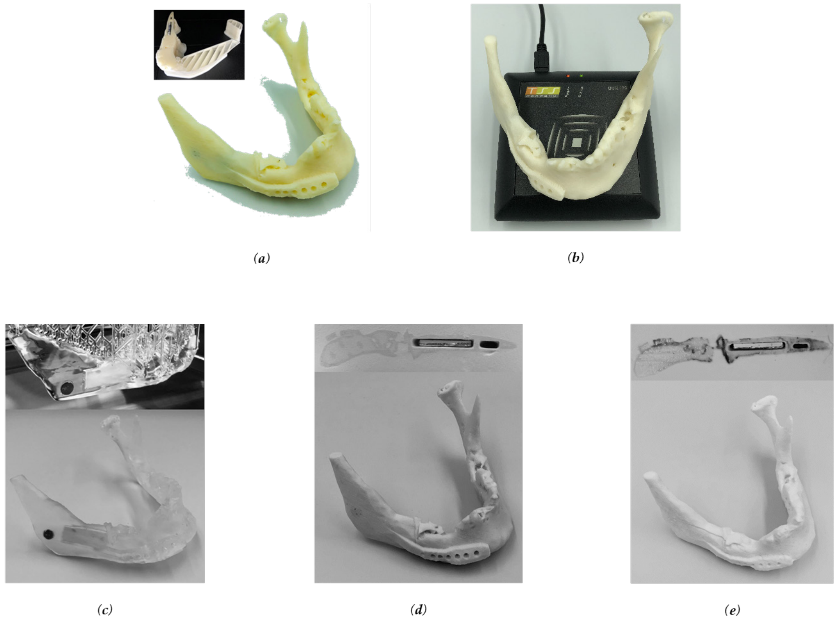


*Figure 4. Additively manufactured mandible with embedded conceptual drug and RFID transponders using: (a) Material Extrusion Method; (b) Radiofrequency identification transmission with Material Extrusion Method; (c) Vat Photopolymerization; (d) Binder Jetting Method; (e) Powder Bed Fusion Method.*

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*Dr. Jan S. Akmal is a postdoctoral researcher at the Department of Mechanical Engineering, Aalto University and at Metal Materials, Electro Optical Systems Finland Oy. His scientific research focuses on the interplay between product development and advanced digital manufacturing with emphasis on decision-making, design, simulation, material characterization, embedding, metrology, and machine learning. He received his D.Sc. degree in Mechanical Engineering in 2022 and M.Sc. degree in Mechanical Engineering in 2017 with distinction from Aalto University. Dr. Akmal has learning experience from Canada, Pakistan, Germany, and Finland. He has gained over seven years of experience working on advanced manufacturing technologies.*

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*Doctoral Thesis*

*Publication 1*

*Publication 2*

*Publication 3*

*Publication 4*