A Cost Model of Part Consolidation for Additive Manufacturing

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Abstract

Part consolidation (PC) is concerned with reducing the number of components in an assembly, and has long been the focus of traditional Design for Manufacture and Assembly guidelines to reduce assembly costs. However, the limitations of traditional processes and correlation between design complexity and cost more often results in products with multiple separate components and complex assembly requirements. Additive manufacturing (AM) processes build parts layer by layer meaning they are capable of manufacturing considerably more complex geometries and do not have the same complexity-cost correlation. PC is described throughout the literature as one of the major benefits of AM, with potential for reducing assembly requirements, reducing inventory and supply chain complexity, and improving product quality by reducing tolerance stack-up. However, there is currently very little empirical evidence provided or means to quantify the impact of PC on costs throughout a product's lifecycle.

This thesis presents an empirical based cost model developed to enable organisations to quantify the impacts of PC on costs for use during the pre-installation phase of AM adoption. The motivation behind this study is the lack of application of advanced manufacturing technology implementation research to AM adoption, and the inability of organisations to systematically consider the potential impact of PC on costs within the justification phase. A single company case study research approach has been used to develop the cost model, basing it on activities within the research host company.

To trial the cost model, embedded redesign case studies were performed to investigate PC in isolation and base the model calculations on empirical evidence. The remaining parameters were defined based on data from the host company. The results show that AM has the potential to significantly reduce part count of sub-assemblies within the host company's products by up to 96%, with a potential 86% cost saving. Contrary to DFMA rules, parts that need to move bodily with respect to other parts and that were originally separated for assembly of other components could both be consolidated using AM. The significant cost savings occur where numerous components are consolidated through PC, thereby eliminating considerable cost elements. This research indicates that the impact of PC on costs could have a significant impact on decisions made with regards to AM adoption, and could provide the justification for further investigation and investment to fully implement and benefit from the technology.

To improve utilisation of the cost model, it was developed into an Excel-based tool enabling organisations to quickly adapt parameters to reflect their own business model and potential for PC

based on redesign case studies. A practical approach based on the methodology used in this research is also developed to help organisations adapt and apply the PC cost model.

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Glossary of terms

AM	Additive Manufacturing
AMT	Advanced Manufacturing Technology
CAD	Computer Aided Design
DED	Directed Energy Deposition
DFA	Design for Assembly
DFAM	Design for Additive Manufacturing
DFM	Design for Manufacture
DFMA	Design for Manufacture and Assembly
DMAM	Dual-Material Auxetic Metamaterials
EBM	Electron Beam Melting
EOL	End of Life
FEA	Finite Element Analysis
FMS	Flexible Manufacturing System
IM	Injection Moulding
JIT	Just in Time
ME	Material Extrusion
MJ	Material Jetting
PBF	Powder Bed Fusion
PC	Part Consolidation
PCB	Printed Circuit Board
R&D	Research and Development
RP	Rapid Prototyping
RT	Rapid Tooling
TO	Topology Optimisation
UV	Ultra-violet
VP	Vat Photopolymerisation

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1 Introduction

Additive manufacturing (AM) was first developed over twenty-five years ago, as a rapid prototyping technology to help reduce development time and costs. AM is defined by the ASTM F42 committee as *"the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methods, such as traditional machining" (ASTM Standard)*. Encapsulating a range of different techniques, recent developments in machine and material capabilities are making AM suitable for end production of fully functional components (Kianian et al., 2016). An overview of different AM processes can be found in Diegel et al. (2014), Bhattacharjya et al. (2014), and Bikas et al. (2016).

Typically, traditional manufacturing process limitations and the development of Design for Manufacture and Assembly (DFMA) guidelines to reduce manufacturing costs resulted in products with multiple parts and sub-assemblies requiring complex assembly. One of the main benefits of AM technologies discussed within existing literature, is the capability for integrative design by building instant assemblies and consolidating the parts and components within an assembly, to reduce part count (Dietrich and Cudney, 2011, Lindemann et al., 2012, Lindemann et al., 2013, White and Lynskey, 2013, Bianchi and Åhlström, 2014, Weller et al., 2015, Yang et al., 2015b, Rodrigue and Rivette, 2010, Hague et al., 2003a). This capability is defined as part consolidation (PC) throughout this thesis, where successful PC results in a reduction in part count.

Considered an Advanced Manufacturing Technology (AMT), AM has the potential to improve manufacturing operations by reducing costs and increasing flexibility and quality (Oettmeier and Hofmann, 2016, Efstathiades et al., 2002). Research into the implementation of AMT gained momentum when organisations were finding they were not delivering the required or expected benefits (Chen and Small, 1994). Research by Lewis and Boyer (2002) found that 50-75% of AMT implementation was being dubbed a failure in terms of quality, flexibility, and reliability. Implementation was defined by Voss (1988) as *"the user process that leads to the successful adoption of an innovation of new technology"* (page 59). Based on the implementation process followed by manufacturing organisations, they defined a 3-phase implementation process: 1) pre-installation, 2) installation and commissioning, and 3) post-commissioning.

Further research into implementation failures found that the pre-installation phase was the most critical for success, ensuring a robust decision-making and planning process (Udoka and Nazemetz, 1990, Hayes and Jaikumar, 1991, Laosirihongthong et al., 2003). Several planning and transfer models were then developed to help provide a structured pre-installation approach and increase

implementation success, such as Chen and Small (1994), Shang and Sueyoshi (1995), Small and Yasin (1997), Efstathiades et al. (2002), and Saberi and Yusuff (2011).

Within the justification stage is the need to identify and quantify all potential benefits and costs of the technology. Failure to do so will mean the organisation is not assessing the true performance of the technology (Small and Chen, 1995, Small, 2006). The nature of AMTs means their impacts and benefits will be both tangible (objective and easily quantifiable) and intangible (subjective and fuzzy) (Small and Chen, 1995, Aravindan and Punniyamoorthy, 2002). A hybrid justification approach is therefore recommended using economic, strategic, and analytic techniques (Aravindan and Punniyamoorthy, 2002, Raafat, 2002, Borges and Tan, 2007, Banakar and Tahriri, 2010, Kreng et al., 2011).

Implementation success was defined by Udo and Ehie (1996) as *"when set goals and objectives stipulated by the adoption strategy are fully realised"* (page 92), i.e. when the implemented technology delivers all the required and expected benefits. Drawing from this research, 3 main stages for pre-installation have been identified by the researcher (Figure 1): evaluating potential benefits, impacts, and applications; justifying adoption of a technology or portfolio of technologies; and planning the implementation process.

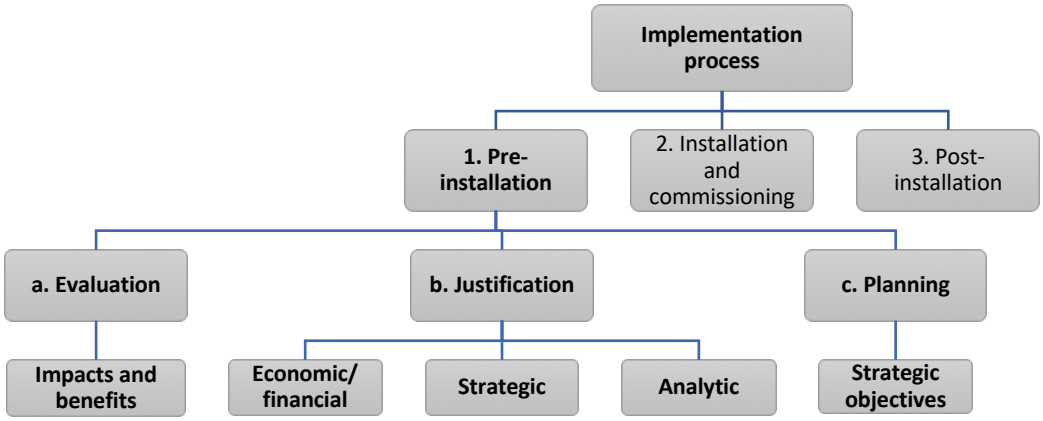


Figure 1: 3 stages of pre-installation based on existing advanced manufacturing technology planning and transfer models and implementation research

Despite the considerable existing research around the implementation of AMTs, there has been very little transfer of pre-installation principles and techniques to AM. Some AM implementation frameworks have been defined, for example Mellor et al. (2014), Achillas et al. (2014), and Deradjat and Minshall (2015), but these assume the business case has already been made and do not provide a structured approach for evaluation or justification.

When considering PC enabled by AM technologies, no consensus exists within the literature on lifecycle benefits or the impact on costs. There is also very little empirical evidence provided to investigate and quantify those benefits, as most case studies are based on single parts. Current AM cost models tend to focus on well-structured process-related costs from build preparation to post-processing, and do not systematically account for PC or wider lifecycle costs. This means that organisations are unable to evaluate and quantify the lifecycle benefits of PC. Without this understanding, a hybrid justification approach could not be applied to AM implementation, reducing potential implementation success.

1.1 Aims and objectives

A central research question was posed for this research: **How significant is the cost impact of PC within AM adoption?** From this central question, 3 sub-questions were defined:

1. Are there existing methods to help organisations successfully implement AM?
2. What are the potential impacts of PC?
3. How do organisations quantify the impacts of PC to help justify AM implementation?

The first two research sub-questions were investigated by reviewing current literature on AM and AMT implementation, and the lifecycle impacts of PC. Two main literature gaps were identified during the literature review:

i. Application of AMT pre-installation principles to AM adoption
ii. Ability of current AM cost models to quantify benefits of PC

In summary, this meant that currently no systematic approach existed for organisations to quantify the potential impacts of PC on costs during the pre-installation phase. This problem led to the definition of four research objectives:

A. Develop a cost model to quantify potential cost savings from PC, for organisations to use during the pre-installation phase of AM implementation
B. Identify the potential for PC using redesign case studies so the model analyses can be based on empirical evidence
C. Evaluate the significance of the cost impact of PC within AM adoption
D. Develop a practical framework for adapting and applying the PC cost model to help justify AM adoption based on PC

A single company case study research approach was used to develop the PC cost model to quantify potential cost savings within *Development* and *Production*. The elements of the constructed model were based on the research host company – Malvern Instruments Ltd (MIL) – who provided financial support along with the Engineering and Physical Science Research Council (EPSRC). MIL design and

assemble precision instruments for material and biophysical characterisation, and were looking to identify opportunities and requirements for successfully implementing AM. Their products are generally complex assemblies with high part count, with functional and material requirements based on the application and environment the instrument will be used in. For example, products used for characterising dry powder material require complex manifolds that must be airtight and designed to reduce air flow turbulence. Instruments characterising wet samples may be in contact with extremely corrosive chemicals, limiting potential manufacturing materials to those with suitable chemical compatibility.

Whilst some of the host company's products may be split into separate components purely due to process limitations and required functionality (e.g. injection moulded manifolds), others have been split up to enable assembly and disassembly of components such as optics and printed circuit boards (PCBs). An overriding theme for the host company is the impact that traditional manufacturing process characteristics and design limitations have had on the design of their products in terms of part count.

Though the host company provided the opportunity to perform this research in an industrial setting ensuring it was empirical and relevant to industry uptake of AM, they did not specify the research focus or objectives. It became clear early in the research process that understanding and being able to quantify the impacts of reducing part count would be crucial to providing the justification they might need to further invest in AM. This research is therefore limited in scope to only consider PC resulting in a reduction in the number of parts in an assembly, and does not take into account any other benefits of AM such as from weight reduction and mass customisation.

Redesign case studies were used as embedded cases to identify the potential for PC for the host company, providing the empirical evidence with regards to a possible reduction in part count achievable using AM. They were redesigns of existing sub-assemblies that had to maintain their current internal forms, level of performance, and assembly with higher level assemblies. No functional or cost optimisation was performed on the case studies as impacts of weight reduction or mass customisation would not be captured due to the focus of this research being part count.

To further limit the scope of this study and due to the focus on the effects of PC, manufacturing process cost models were not constructed in this research. Costs can vary significantly between AM processes due to differences in machine and material cost, build time, and post-processing requirements and should therefore be considered on a case by case basis. Including these in the model would also have limited it to one type of manufacturing process. At the pre-installation phase

of implementation where companies are still investigating AM as a group of technologies, it is unlikely the adopting organisation would have chosen one particular process or machine.

The model was trialled on the host company using the redesign case study results and existing data to define the remaining cost and time parameters. The results were used to evaluate and discuss the impact of AM on traditional Design for Manufacture and Assembly (DFMA) guidelines, and the significance of the cost impact of PC within AM adoption for the host company and other adopting organisations. The model was developed into an Excel based tool, and a practical framework was defined for adapting and applying the model to help increase utilisation.

1.2 Thesis structure

This thesis is structured with a conventional sequence of chapters: literature review, methodology, results, discussion of results, and conclusions. The literature review (second chapter) starts with the background literature to AM focusing on capabilities, benefits, and process limitations of AM. A focal section on the benefits and economic implications of PC and existing case studies resulting in a reduction in part count is then presented. A second focal section covers the implementation of manufacturing technologies, based on advanced manufacturing technology implementation research along with existing AM implementation frameworks and current AM cost models. The research question and objectives defined in the previous section combine these two main focal areas, to be able to evaluate and quantify the benefits of PC within the implementation process of AM adoption.

The third chapter outlines the methodology followed to develop and trial the PC cost model. First, the elements of the model are defined based on existing literature and the *Development* and *Production* activities of the host company. The cost model is developed by defining these elements in terms of a cost rate or direct cost. The model is trialled on the host company by defining the cost and time parameters and identifying the potential for PC from the redesign case studies to define the number of parts in an unconsolidated and consolidated design. The redesign approach followed is also summarised along with the analyses to be performed and methodology for improving utilisation of the cost model.

The fourth chapter outlines the research results in two main streams – the redesign case studies and the model trial results in terms of potential cost savings from PC for the host company. These results are then discussed in the fifth chapter in terms of designing for PC, the impact of PC on costs, the implications of the research results on the pre-installation phase of AM implementation, and

concludes with the development of a practical approach for other adopting organisations to justify AM adoption based on PC.

The sixth chapter outlines the main conclusions relating back to the original research objectives, and the limitations of the research with suggestions for further work.

Figure 2 graphically summarises the structure of this thesis including the main sub-chapters.

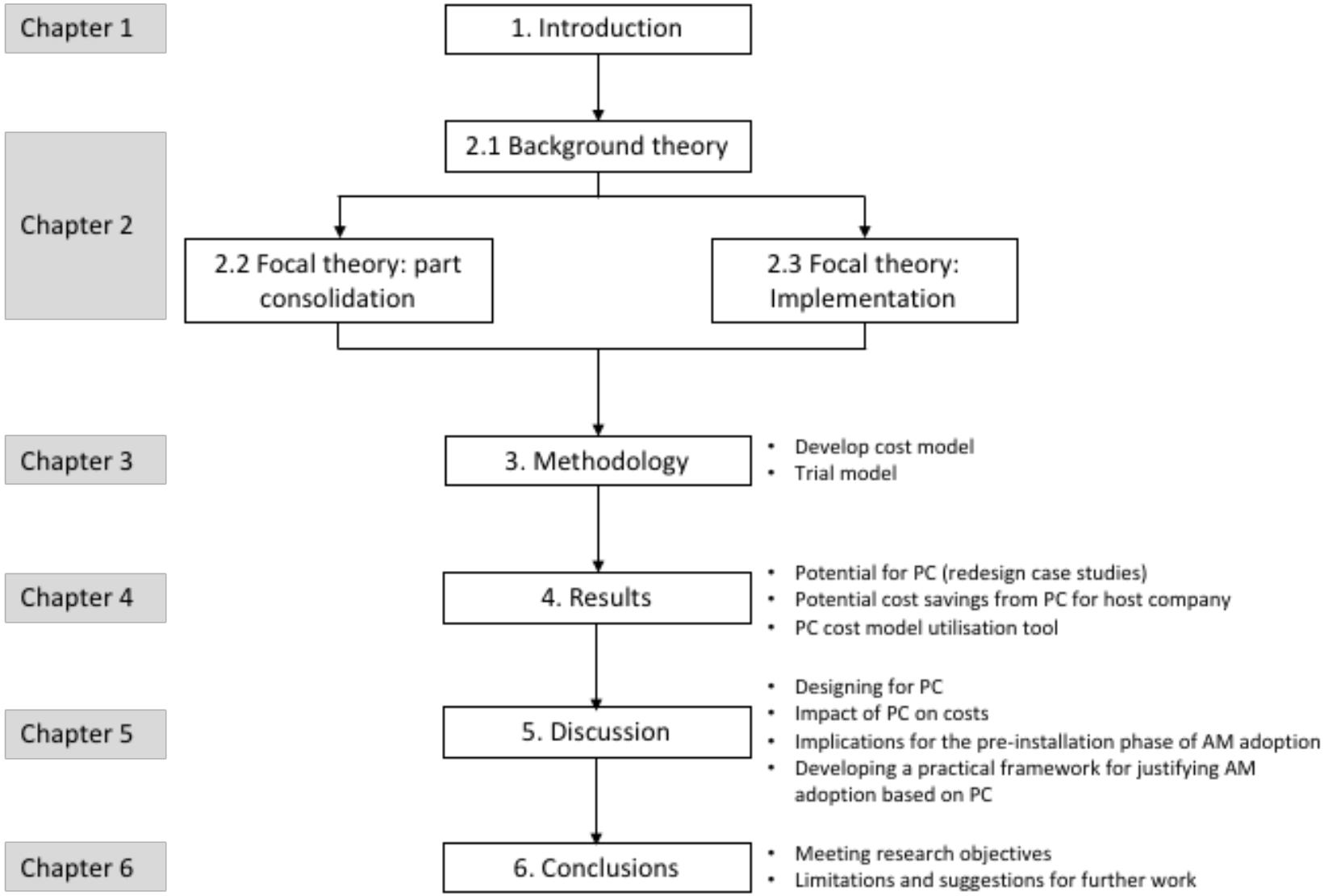


Figure 2: Structure of thesis chapters

1.3 Published works

Two peer-reviewed research papers were written during this research. The first was a contribution to the 2017 Solid Freeform Fabrication (SFF) Symposium, which was presented by the researcher titled "How significant is the cost impact of part consolidation within AM adoption?" (Stevenson et al., 2017b). The second was a paper for the Rapid Prototyping Journal which as of October 2017 is still awaiting confirmation of review/acceptance, titled "A cost model of part consolidation for additive manufacturing" (Stevenson et al., 2017a). They outline the main objectives and justification of the research, along with some results and a constrained discussion of the results.

2 Literature review

The purpose of this literature review is to identify and evaluate existing knowledge on PC enabled by AM processes, the implementation of new manufacturing technology, and how the potential benefits of PC can be properly considered when making decisions about AM adoption. The literature review will therefore be structured as follows. The first section will give an overview of the capabilities and benefits of AM in terms of design complexity, economic one-off and low volume production, on-demand and decentralised production, reduced barriers to entry, AM-enabled business models, and potential impact on the value chain. It will conclude with a section focusing on PC and its potential economic implications.

A summary of limitations related to the layering build method and design methodologies will then be given. The next section will review literature on the implementation process of new technologies, beginning with a definition of implementation and the research on advanced manufacturing technology (AMT), followed by AM implementation research with a discussion on the limitations of current AM cost models to consider full lifecycle impacts from PC on costs.

2.1 Background literature – capabilities, benefits, and process limitations of AM

AM changes the design-build-deliver stages of a product's lifecycle; disrupting manufacturing, restructuring modern supply chains, and creating new rules of competition through economies of one (Petrick and Simpson, 2013, Achillas et al., 2014). Subtractive manufacturing processes impose fundamental restrictions to design due to tool access and fixture point requirements (Flynn, 2012). The more complex a design, the more material needs to be removed increasing the number of machining operations and subsequent manufacturing cost due to increased setups, tool changes, and overall machining time (Conner et al., 2014). Tooling manufactured for forming processes such as injection moulding and casting have the same limitations, as well as the need to consider the removal of the formed part from the tooling. These characteristics have required engineers and designers to circumnavigate complex process limitations during the design phase resulting in sub-optimal components in terms of form and/or function. As a consequence, components are bulkier than required and products are split up into multiple separate and simplified parts to reduce manufacturing complexity (Diegel, 2014).

Instead of starting with a solid block and removing material to create the desired form, AM slices a digital representation of a 3D component into 2D slices of predefined thickness, and builds each layer sequentially. This helps simplify geometry making AM capable of producing parts free from almost all

geometric constraints (Petrovic et al., 2010, Vayre et al., 2012). Organic shapes can be more easily manufactured, draft angles ignored, and internal cavities created where conventional processes could not reach (Flynn, 2012, Hague et al., 2003a) enabling designers to manufacture the product they imagined with almost unlimited complexity (Hague et al., 2003a). According to Thiesse et al. (2015), manufacturing systems can be distinguished by their flexibility and efficiency; where flexibility refers to its outcomes (e.g. product range) or reacting to changes in demand. The main benefits of AM processes come from their layering build method requiring no tooling, jigs, or fixtures. Literature outlining the capabilities and benefits of AM are varied in their approach depending on the focus of the research. Examples can be found in Oropallo and Piegl (2015), Weller et al. (2015), Gao et al. (2015), Ashour Pour et al. (2015), and Bhattacharjya et al. (2014).

2.1.1 Design complexity

2.1.1.1 Lattices, honeycombs, and small-scale structures

Topology optimisation uses geometry to optimise an objective function subject to constraints and boundary conditions (Leary et al., 2014). Far more efficient designs can be achieved in terms of both the amount of material used and functional performance. This can be particularly beneficial when designing for weight load optimised components and using lattices and honeycomb structures for applications such as aerospace, automotive, and medical (Vayre et al., 2012).

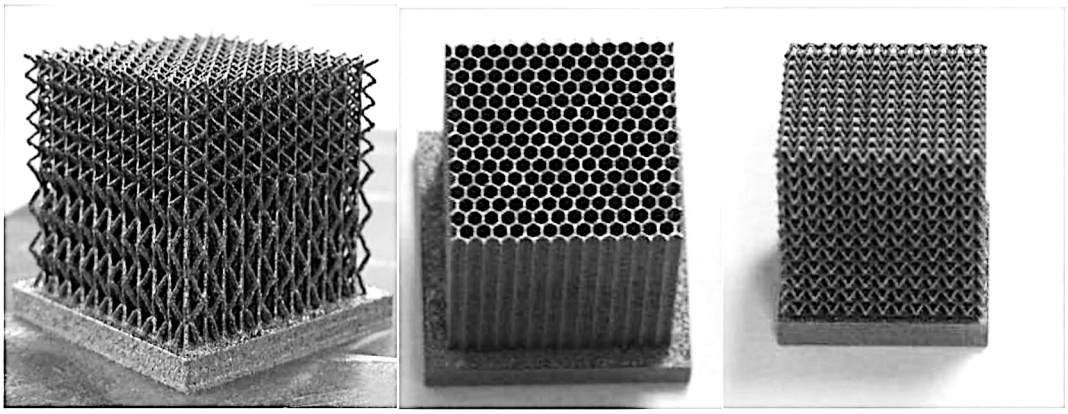


Figure 3: Different types of structures fabricated using directed energy deposition (courtesy of LaserCUSING): multi-size cubic cell, honeycomb cell, and single-size cubic cell. Image taken from Petrovic et al. (2010)

An investigation by Petrovic et al. (2010) found that AM could be used to produce lightweight aerospace and automotive parts by manufacturing structures such as those shown in Figure 3, helping

to reduce the 'buy-to-fly' ratio and fuel consumption during use. Tomlin and Meyer (2011) used topology optimisation for an aerospace part using finite element analysis (FEA) to reduce its weight (Figure 4) but concluded that optimisation would need to occur on very large parts or across many small parts to make a big enough weight reduction to justify the use of the technology.

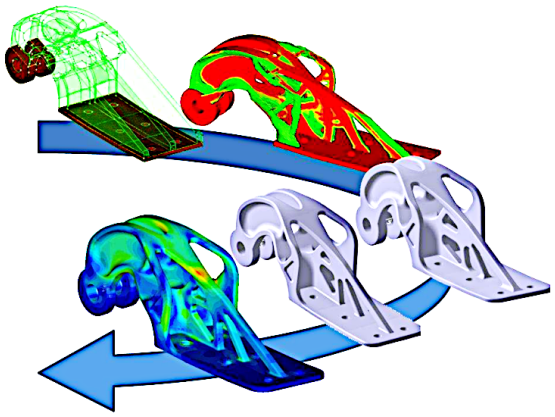


Figure 4: Topology optimisation of the Airbus A320 nacelle hinge bracket using finite element analysis (FEA). Image taken from Tomlin and Meyer (2011)

Wang et al. (2016b) reviewed the application of topology optimisation of porous metal for bone scaffolds and orthopaedic implants concluding that AM was *"the most promising and disruptive technology in the fabrication of porous orthopaedic implants* […] *that mimic human bone*" (page 137). Applications for this capability have also been explored by Riza et al. (2014), Zargarian et al. (2016), Taniguchi et al. (2016) and Costa et al. (2015) where they have found major benefits of using AM for implants due to its porosity and honeycomb structures for improved bone regeneration and ingrowth, and strength to cope with cyclic loading imposed during daily activities. Wong et al. (2007) designed four heat sinks with improved performance using complex lattice structures that could not be manufactured using traditional processes (Figure 5).

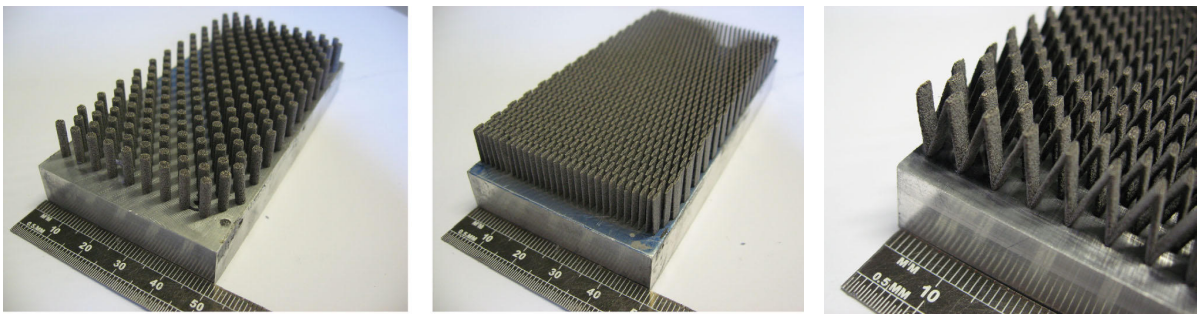


Figure 5: Heat sinks of different designs and materials exploiting the design freedom of AM for improving heat transfer capability. Image taken from Wong et al. (2007)

Metamaterials can also be used to optimise performance and were recently defined as *"assemblies of small-scale structures that obtain their bulk properties from the shape and arrangement of the structures rather than from the composition of the material itself"* (Schumacher et al., 2015; page 136:1). Originally introduced within the electromagnetic materials field, the development of structure design and processing methods have extended their application to mechanical behaviours including phononic crystals, auxetic materials, and acoustic metamaterials (Lee et al., 2012). Manufacturing these has previously been difficult using conventional processes due to inherent process limitations and the cost penalties associated with increasing complexity.

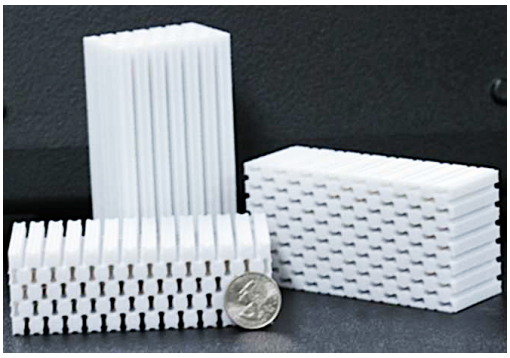


Figure 6: Manufactured anisotropic metamaterials using Material Extrusion. Image taken from Garcia et al. (2012)

Garcia et al. (2012) and Isakov et al. (2016) investigated the use of AM for creating anisotropic meta-materials with potential for novel electromagnetic devices which could not be created using conventional processes (Figure 6). Yang et al. (2015a) investigates the mechanical properties of various 3D re-entrant honeycomb auxetic structures printed using two different AM technologies to develop a multi-directional model to enable the auxetic cellular structure to be applied for loading cases in multiple direction (Figure 7).

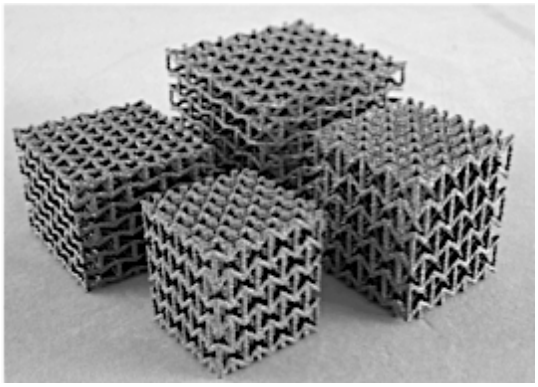


Figure 7: Re-entrant auxetic sample by electron beam melting (EBM). Image taken from Yang et al. (2015a)

Wang et al. (2015) fabricated dual-material auxetic metamaterials (DMAM) and found they exhibited better properties than using a single material AM process. Following on from that, Wang et al. (2016a) then investigated an application for DMAM to bridge the difference between the mechanical properties of polymer and soft-tissues to create metamaterials for patient-specific tissue-mimicking phantoms. Aware of the varying capabilities and limitations across different AM processes, Schumacher et al. (2015) developed a method for defining different small-scale microstructures for creating objects with spatially varying elastic properties, matching the structure design to the material and capabilities (e.g. accuracy and resolution) of the printer used to build them (Figure 8).



Figure 8: Computation and single-material fabrication of small-scale structures that approximate the desired elastic behaviour. Image taken from Schumacher et al. (2015)

AM has also been used to fabricate and test biomimetic materials which are based on structures found in nature. The research into different types of structures have focused on achieving properties such as energy dissipation using biomimetic staggered composites (Zhang et al., 2015a), improved shear strength of osteochondral scaffolds (Zhang et al., 2015b), and abrasion resistance by mimicking the teeth of Chitons (de Obaldia et al., 2015). Though AM can easily fabricate such complex structures, defining the required structures can be much more complicated and time consuming. This issue has been approached by developing design methods and software to more easily define the boundaries

and develop an optimised structure (Gardan and Schneider, 2014, Tang et al., 2015, Rezaie et al., 2013).

2.1.1.2 Pre-defined material deposition for multi-material components

Recent developments in AM technology and machines have made multi-material printing a reality, where different materials can be placed in predefined areas of a part during a build cycle. For material extrusion, this concept is not particularly new as most printers above the home fabrication classification are based on dual material printing of a build material and a sacrificial support material for overhanging geometries. This support material is then usually removed post-process leaving a single material component. Developments have also been made where the build material polymer is 'loaded' with another compound. For powder bed fusion processes, loaded nylon particles have been developed which have varying weights of carbon or aluminium (Wood, 2016). The nylon is processed in the same way but the material it is loaded with will help increase strength and temperature resistance.

Material jetting prints in multiple materials by mixing blends of UV-curable polymeric resins and co-depositing them from multiple printing heads to create parts with spatially graded properties (Stansbury and Idacavage, 2016). Different shore A hardness rubbers and transparent materials can be deposited alongside resins simulating grades of ABS by mixing resins for high temperature and toughness.

This capability has been explored by Pereira et al. (2014b) who developed an automatic algorithm for defining internal fibres to route light between arbitrary surfaces within a model. It continued the work of Willis et al. (2012) who first showed that optical fibres could be printed but relied on a complicated manual design process. Both utilise multi-material printing of two materials with different indices of refraction and the light is then transmitted through the model from point to point by total internal reflection. The relatively poor mechanical properties of these photopolymers is currently limiting this multi-material capability to prototyping applications (Wood, 2016). This makes it difficult to know what the potential could be for future products. What does not appear to have been discussed in any detail is the ecological impacts of these multi-material products in terms of disassembly, reuse, or recycling at end of life.

2.1.1.3 Sequential layering of material for operational mechanisms and embedded components

Traditional operational mechanisms rely on moving joints and can be incorporated into AM parts by carefully controlling the fabrication of each layer to create a captive assemblage linkage (GIBSON, 2010, Gao et al., 2015). Lipson et al. (2004) for example used material extrusion (fused deposition modelling (FDM)) to fabricate functional, accurate, pre-assembled reproductions of several Reuleaux-Voigt kinematic models. These models incorporated a range of different mechanisms including pumps, ratchets, joints, links, gears, springs, worms, nuts, and bolts (Figure 9).



Figure 9: Functional, pre-assembled historic kinematic models and machines incorporating a range of mechanisms including pumps, ratchets, gears, joints, springs, nuts, and bolts. Image taken from Lipson et al. (2004)

Calì et al. (2012) later investigated an approach for using computational geometry operations to model the degrees of freedom of different joints, and printed parts with an optimised joint design using powder bed fusion (Figure 10). Bächer et al. (2012) developed a model for automatically generating articulated models with ball-and-socket or hinge joints that are different to most case studies as they are posable (i.e. will maintain their manipulated position) (Figure 11).



Figure 10: Test joint manufactured to explore physical properties of various joint designs. Image taken from Cali et al. (2012)

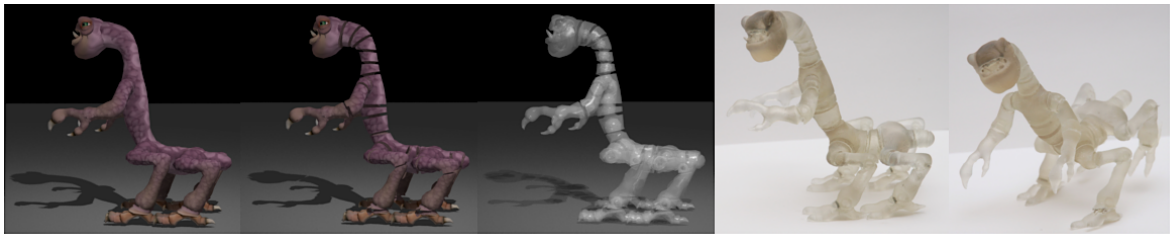


Figure 11: Automatic generation and fabrication of a posable articulated model utilising ball-and-socket or hinge joints. Image taken from Bächer et al. (2012)

Compliant mechanisms however do not rely on moving joints but *"utilise deformation of flexible members to transfer motion, force, and energy without discrete hinge elements"* (Gaynor et al., 2014; page 980). An example of this is for living hinges which can be fabricated by controlling the wall thickness of the compliant sections (Gibson et al., 2010a). Multi-material processes can also be used such as in Gaynor et al. (2014) who designed and manufactured a multi-material 3-phase inverter using a rubber-like material to increase its deflection (Figure 12).

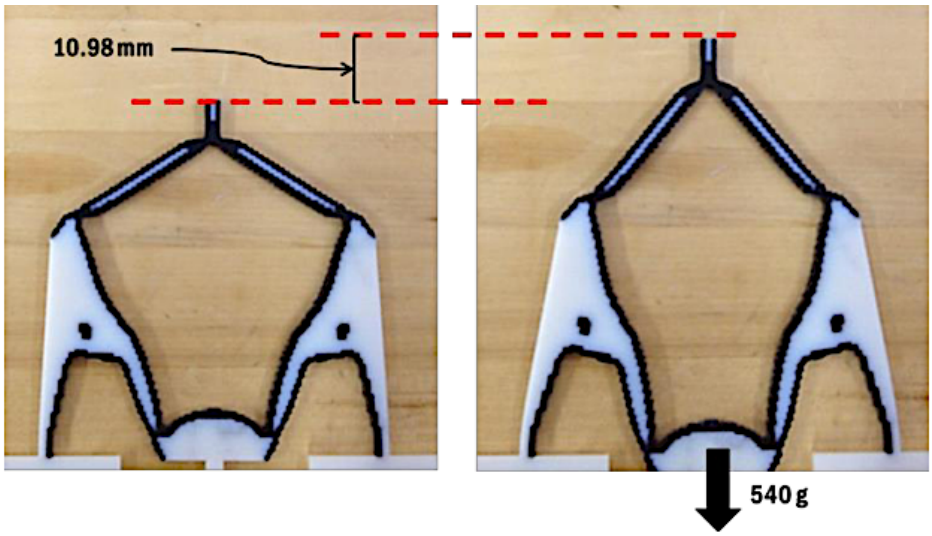


Figure 12: 3-phase inverter using a rubber-like material to increase deflection under load. Image taken from Gaynor et al. (2014)

The layer-wise methods of AM means users can access the entire volume of a part throughout the build process (Meisel et al., 2015). The also enables components such as electronics, nuts, bolts, gears, and circuit boards to be embedded into the part (GIBSON, 2010) allowing the creation of novel products and integrated assemblies (De Laurentis et al., 2002). Hossain et al. (2016) embedded a non-intrusive sensor into an energy system build using electron beam melting (EBM) by stopping the build

when it reached the required level. However, they identify that more work needs to be done to understand the impact on the bond of the layers from stopping and re-starting the process.

De Laurentis and Mavroidis (2004) manufactured a robotic hand assembly incorporating functional mechanisms and embedding components within the part during the build cycle (Figure 13). Meisel et al. (2015) take a similar mechanical design but embed shape memory alloys to investigate their potential use as actuators using both compliant and traditional pin-joint mechanisms (Figure 14). Sensors, displays, and illumination elements have been embedded into multi-material cases (Figure 15) for interactive devices with custom optical elements by Willis et al. (2012).

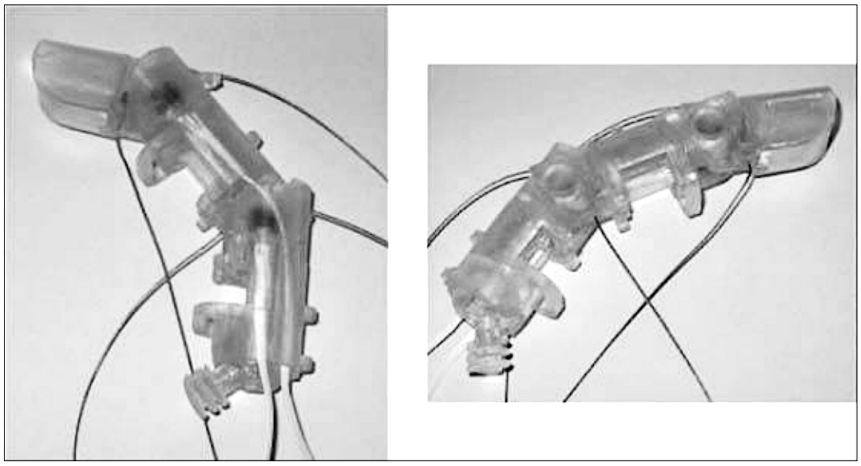


Figure 13: Instant assembly of a robotic finger with components embedded during the build cycle. Image taken from De Laurentis and Mavroidis (2004)

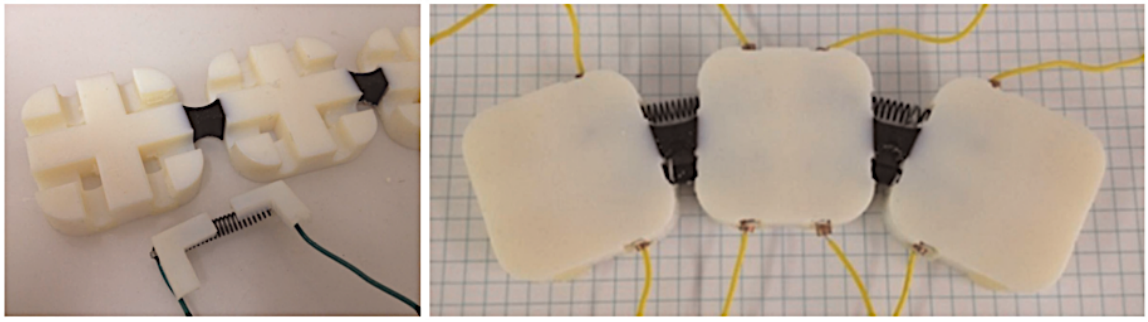


Figure 14: Compliant and pin-jointed assemblies with embedded shape memory alloy to investigate the potential for actuators. Image taken from Meisel et al. (2015)

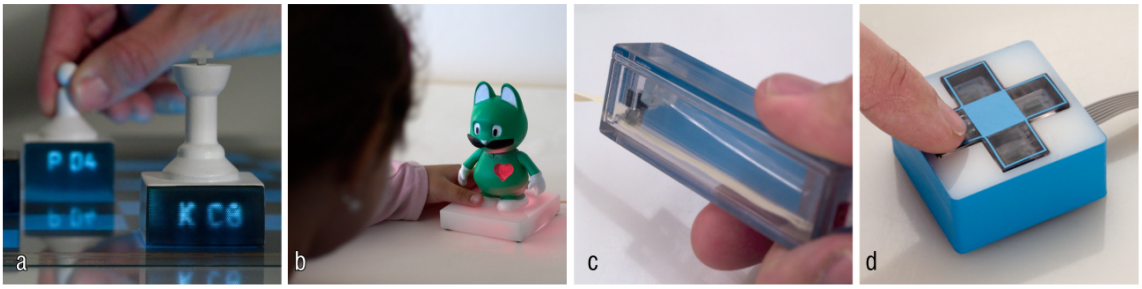


Figure 15: Custom optical elements embedded in interactive devices a) light pipes b) internal illumination techniques c) custom optical sensors d) embedded electronics. Image taken from Willis et al. (2012)

2.1.2 Economic one-off and low volume production

Reducing time-to-market of new product introductions is critical for sustaining competitive advantage and increasing market share – particularly in high technology industries (Datar et al., 1997). This requires companies to be agile and respond quickly to unpredictable changes (Sangari et al., 2015, Cegarra-Navarro et al., 2015). Without the economies of scale and lead times associated with traditional processes, AM can be used as a rapid prototyping (RP) tool to help reduce development time (Kochan et al., 1999, Cozmei and Caloian, 2012, Beyer, 2014). Prototypes can be made for evaluation to catch errors early on and optimise the design (Stucker, 2011), and enable production to begin as soon as the product is released without having to wait for tool manufacture (Bhattacharjya et al., 2014, Atzeni and Salmi, 2012).

Low volume direct-from-CAD manufacturing also means that any design changes required post-introduction can be implemented quickly, without requiring changes to tooling or existing stock to be modified or scrapped. This helps increase flexibility and reduce the risk associated with new product introduction by reducing the cost and time for agile development (Oettmeier and Hofmann, 2016, Bogers et al., 2015, Cozmei and Caloian, 2012).

AM can also produce rapid tooling (RT) for traditional processes direct from 3D CAD data, having significant impacts either directly or indirectly on the time and cost associated with tool production (Simchi et al., 2003, Rahmati, 2014, Levy et al., 2003). Conventional tooling has a long lead time, high complexity and cost correlation, and low flexibility to accommodate future design changes. These factors can have a significant impact on the release date of new products, the designs they can manufacture, and the cost of low volume production where the tooling costs are amortised over a small number of parts.

RT can be used for low volume prototyping and end production, and as “bridge tooling” to enable production to begin whilst the conventionally made tooling is being designed and manufactured (Noble et al., 2014), and could be more ecological (Lušić et al., 2015). Using AM means that its capabilities for internal complexity can also be used to manufacture conformal cooling channels helping to reduce cycle time (and therefore production cost) and improve part quality (Dimla et al., 2005, Park and Pham, 2009). Though this does take some advantage of the complexity capability of AM, processes requiring tooling still impose inherent restrictions to part design due to the nature of the manufacturing process, limiting which additional capabilities can be taken advantage of (such as topology optimisation and operational mechanisms).

As the goods markets shift from homogenised to individualised, companies are under increasing pressure to offer customised products in order to compete (Eyers and Dotchev, 2010). Conventional processes requiring high cost tools and fixtures result in economies of scale which make customisation expensive. Companies are now able to offer products which are customised to an individual’s needs in terms of function, fit, appearance, and interaction far more cost-effectively using AM than with traditional processes (Conner et al., 2014, Berman, 2012, Khajavi et al., 2014). Eyers and Dotchev (2010) give an overview of some of the most promising applications of mass customisation in different industries including custom implants for dentistry, orthopaedics, and crania-maxillofacial; hearing aids with custom shape, colour, removal features and ventilation; and lamps where customers can choose the size, colour, and text detailing.

For medical applications, the driver for persuing AM has been to use patient specific scan data using computed tomography, magnetic resonance imaging, and ultrasounds for customised implants and surgery aids (Marro et al., 2016, Guy et al., 2016, Malik et al., 2015). To overcome potentially long lead times of AM processes, Kim and Jeong (2015) looked at combining injection moulding (IM) with customised AM for a hybrid production process where the focus was on reducing cycle time by reducing the volume of the AM part.

2.1.3 Flexible machines enabling on-demand decentralised production

Traditional supply chains usually rely on linear hand-offs between distributed manufacturers (Petrick and Simpson, 2013) and are structured around the capabilities (and limitations) of conventional manufacturing processes used for mass production. These supply chains generally have large inventory close to the point of consumption with high warehousing, inventory obsolescence, and capital costs related to slow-moving parts (Khajavi et al., 2014). Unpredictable demand, multiple

product generations, and increasing product variation makes supply chains even more complex and unable to respond efficiently.

There are two main methodologies investigated within AM supply chain research: agility (responsiveness/flexibility), and lean (efficiency). With pressure from customers for reduced lead times, supply chain agility is concerned with reducing lead times. It is considered a key element of competitive advantage and a determinant of survival and long-term success (Sangari et al., 2015) by enabling organisations to react quickly to demand and change product outcomes (Thiesse et al., 2015). Lean is focused on efficiency and reducing waste and can be indicated by lead time and variable cost incorporating just in time (JIT) methodologies (Thiesse et al., 2015).

Traditionally, products are manufactured and assembled far from the location of the customer due to process limitations and dedicated tooling requirements (Thiesse et al., 2015). AM is an inherently flexible technology with no tooling lead times to consider or large production volumes required to reduce costs. It is also digital which significantly reduces the need for investment due to cheaper, flexible machines with no tooling, jigs or fixtures (Würtz et al., 2015). On-demand production can help reduce lead times and waste associated with inventory storage requirements, obsolescence, and capital costs – with a significant impact on profitability (Atzeni and Salmi, 2012, Achillas et al., 2014, Kietzmann et al., 2015, Bogers et al., 2015, Beyer, 2014, White and Lynskey, 2013). Being inherently flexible, AM machines could be distributed in locations outside the traditional centralised production facilities, enabling distributed production and localised manufacturing (Stucker, 2011). The concept of AM being a "*leagile*" (both lean and agile) technology was introduced by Tuck et al. (2006). The benefits of decentralised production can be summarised from Khajavi et al. (2014) and Bogers et al. (2015) as:

- Greater responsiveness and flexibility
- Improved decision making based on more accurate information from local conditions
- Improved efficiency and reliability
- Lower shipping and inventory-related costs
- Less sophisticated ERP systems
- Reduced inventory
- Decreased forecasting dependency and lead times

Research covering on demand decentralised production has so far been driven by the spare part supply chain for aerospace and automotive industries, where downtime constitutes a considerable cost to the manufacturer. Typically these supply chains rely on high volume production, long distance transportation, and extensive warehousing with a significant risk of spare parts becoming outdated or unusable (Rommel and Fischer, 2013). Khajavi et al. (2014) evaluated AM for the spare parts supply chain of the F-18 Super Hornet fighter jet but concluded that a centralised supply chain is still

preferable due to the high cost of machines and long production cycles. This is also backed by Ashour Pour et al. (2015) who identified that high labour and machine costs will limit the potential for decentralising spare part supply.

Bogers et al. (2015) and Bogers et al. (2016) suggest a hybrid *"leagile"* approach to centralised production which can still enable some benefits of AM across certain products or parts. A lean approach can be used for standard products with low variety and stable demand, and agile for personalised components with turbulent demand. They also introduce the concept of a *"glocalised"* supply chain which are local independent, self-sufficient supply chains setup around the globe.

2.1.4 Reduced barriers to entry to enable co-design and prosuming

AM offers a unique opportunity to enable companies to take advantage of innovations, ideas, and resources outside the company boundaries (Bogers et al., 2016). As a digital technology with considerable design freedom, it increases the interactivity between design and production with a direct link between consumers and manufacturers (Petrick and Simpson, 2013) enabling customers to co-design products that fit their needs and demands (Weller et al., 2015). This results in a joint creation of value between customers and companies (Gao et al., 2015) and could be utilised as an additional source of innovation helping to improve the design (and value) of products and services (Würtz et al., 2015).

The expiration of patents around material extrusion technology led to the development of much cheaper and open source printers at 0.1% to 10% of the cost of industrial machines (Stucker, 2011). This reduced the barriers to entry for print hubs and home fabrication; resulting in the *"democratisation of production"* enabling new alternative production routes for manufacturers (Geraedts et al., 2012). Print hubs could radically localise the production, sourcing, and distribution of products and could utilise smaller-scale shipping methods for getting the product to the end consumer (Petrick and Simpson, 2013). Consumers could also take over production of the products they buy using personal home printers – making them *"prosumers"* (Bogers et al., 2015, Rayna and Striukova, 2016, Thiesse et al., 2015). The prosumers become an active member in the supply chain network enabling companies to bypass the (physical) distribution stage and associated costs (Rayna and Striukova, 2016, Würtz et al., 2015).

However, Thiesse et al. (2015) point out that some products are too difficult to manufacture and assemble by consumers due to the required technical knowledge and the risk they may not fit first time. Rayna and Striukova (2016) believe even with the development of HD multi-material printers,

home fabrication ("*prosuming*") will likely remain uneconomical for mass-consumed products. Issues such as intellectual property and legal implications will also need to be considered by manufacturers, policy makers, and legislators as it will be much harder to maintain control of designs and outputs due to the digital nature of the technology and the range of machines and materials (Kietzmann et al., 2015, Bogers et al., 2016).

Democratising the supply chain however could lead to a new source of competition to manufacturers by promoting "*collaborative innovation and peer-production ecologies*" (Thiesse et al., 2015; page 146) enabling user innovation and entrepreneurship around design, machine development, and business generation (Stucker, 2011). Products can now be designed, printed, and sold more easily and cheaply than before, by using personal knowledge and equipment, or utilising services offered by print hubs with no requirements for any capital investment before manufacture begins. According to Rayna and Striukova (2016), this could trigger a significant increase in competition for current design and manufacture companies. Customers will be faced with even more choice which will likely result in a reduction in prices making it difficult to find a suitable business revenue model.

2.1.5 Implications of AM for business models and the value chain

AM has huge potential for impacting the design and supply of products. However, its disruptive nature implies the need for important changes to the technical and managerial aspects of a company's business model to capture its value (Bogers et al., 2016, Rayna and Striukova, 2016). Decentralising manufacturing operations for example could be majorly beneficial for a company but it also brings challenges with regards to management and information flow (Khajavi et al., 2014). New business plans can be developed at the hobby, prototyping, and short-run production level based around localisation and accessibility but require significant changes to the supply chain (Bogers et al., 2015, Gao et al., 2015). Thiesse et al. (2015) suggests that for companies to know how to react to AM, research needs to explore which aspects of business models are influenced, with a holistic view of the value chain based on specific business strategies.

The value chain can be used to describe an organisation's business model in terms of its ability to propose, create, deliver, capture, and communicate value; and plays a key role in the extent to which a new technology can create competitive advantage. A study completed by Bhattacharjya et al. (2014) found that companies who had adopted AM reported an increase in value creation through improved lead times and positive changes in business-to-business interactions; as well as needing additional resources, staffing, and training. Profitability can also be improved by capturing more value; reducing overall production costs by utilising on-demand production to eliminate inventory related expenses

and create a positive cash flow, and reduce time to market through faster product innovation and introduction (Achillas et al., 2014).

Rayna and Striukova (2016) looked at the impacts along the value chain of the four levels of AM adoption: rapid prototyping, rapid tooling, direct manufacturing, and home fabrication. Direct manufacturing and home fabrication enables parts to be designed for AM meaning the functional and supply chain benefits can be achieved, with significant impacts along the value chain summarised in Table 1. However, despite the potential for creating more value, they explain that capturing the value becomes more difficult. A major consideration for home fabrication and co-design for example is whether customers will still be willing to pay more if they are taking over processes which would originally have been paid for by the company. Khajavi et al. (2014) suggest a balance to customer satisfaction by offering more value from reduced lead times and personalised products with increased functionality. Good service should also help prevent customers from reverse engineering the products which would make it difficult for companies to maintain their intellectual property (IP) rights (Kietzmann et al., 2015).

Table 1: Summary of impacts of direct manufacturing and home fabrication along the value chain from adapted from Rayna and Striukova (2016)

Value chain	Direct manufacturing	Home fabrication
Value proposition	Improve product and service offering New pricing models for customised products	More products and services as no distribution to consider
Value creation	Large scale personalisation using co-design for higher product value Flexible AM printers for more opportunity and choice (workflow, logistics, materials and quality)	Crowd-souring and mass customisation have impact on value proposition and value delivery, triggering greater adoption of home printers and positive feedback loop to value creation
Value delivery	New distribution channels – e.g. print hubs and on-demand production - no transportation or physical storage costs until the order is made	Every consumer with a printer becomes part of the value network and a potential distribution channel – more economical target market segments
Value capture	Altered cost structure from lower fixed costs and higher marginal costs	Cost structures change as manufacturing and distribution is on customers –

	AM for customised or slow moving/low value parts with high distribution and storage costs Positive cash-flow (on-demand production)	companies will be forced to rethink their revenue models and profit allocation

According to Würtz et al. (2015), using AM for mass customisation enlarges the "classical" product development process (PDP) towards both the front- and back-end process where customers become part of the design team and/or supply chain network respectively. This will in turn impact the value chain throughout the product lifecycle, but will depend on which level of the bill of materials (BOM) the customised AM part is placed as to whether it will result in value increase or value decrease. They explained that, for example, utilising the customer for production would result in value decrease for the manufacturer but could be suitable when maintenance is not part of the business model, the part is not critical for functionality or security, and needs cheap and fast Global spare part delivery. Production by the supplier could be suitable for critical parts requiring maintenance as it will increase value but also increase manufacturing costs.

Weller et al. (2015) analysed the potential effects of AM's four key principles (versatile manufacturing, free customisation and flexibility, free complexity, and reduced assembly requirements) on a firm's payoff function using Milgrom and Roberts (1990) model. They concluded that profits can be increased by manufacturing customised products at lower costs with potential for achieving a price premium. Their analysis also showed that potential markets for AM could be characterised by four patterns: small production output, high complexity, high demand for customisation, and spatially remote product demand.

The potential impacts of AM on the value chain make it clear to see how adopting the technology might help increase their competitive advantage. However, ensuring the potential value is captured can be much more difficult (Bogers et al., 2016, Rayna and Striukova, 2016). Competitive advantage can be transient requiring companies themselves to be agile in order to seek out and exploit opportunities (Conner et al., 2014). Rayna and Striukova (2016) introduce the concept of *"bringing the RP paradigm to business model innovation"* (page 214) as AM makes both lateral and vertical movement less risky due to reduced capital investment and on demand manufacture. Business models can be tried out at much lower costs enabling companies to rapidly test designs and ideas. Firms can then be adaptive, with business models capable of moving up, down or sideways as required (Figure 16).

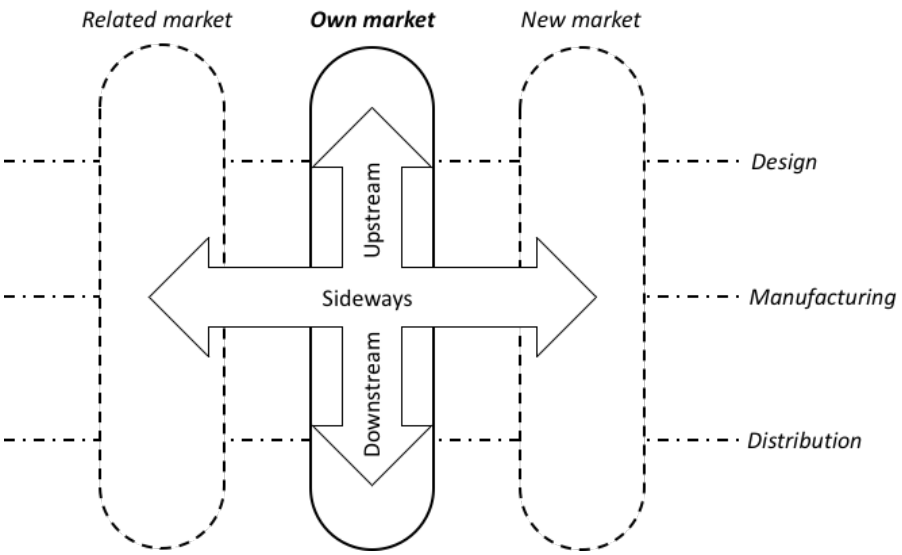


Figure 16: AM-enabled adaptive business models. Image taken from Rayna and Striukova (2016)

2.1.6 Design for AM (DFAM)

AM technology has removed many of the constraints that might have previously prevented a designer from making the product they imagined (Diegel et al., 2010) by utilising undercuts, variable wall thickness, screws, deep channels, blind holes, high strength to weight ratio, static, dynamic parts consolidation and more (Atzeni and Salmi, 2012). However, the gap between the possibilities of AM and available design guidelines, tools, and standards of best practice has been identified as a serious limitation for AM (Geraedts et al., 2012, Gao et al., 2015). According to Beyer (2014); *"innovative approaches toward design are required to capture the full potential of AM"* (page 064701-1). The traditional design guidelines which sought to reduce redesigns and cost pitfalls are not valid for AM processes, changing the focus from Design for manufacture (DFM) to "*manufacture for design"* (Petrick and Simpson, 2013).

Despite the focus being on achieving novel properties and product capabilities, designers must also consider the process specific limitations and the impact of the design on quality, efficiency, and cost (Leary et al., 2014, Ponche et al., 2014). Rosen (2014) explains the objective of DFAM as *"maximising product performance through the synthesis of shapes, sizes, hierarchical structures, and material compositions, subject to the capabilities of AM technologies"* (page 225).

Some processes have characteristics which will fundamentally limit potential design freedom such as those using non-soluble support structures requiring access for removal post-process. A recent review of AM design theory and methodology can be found in Yang and Zhao (2015), who classified AM related design methods into design guidelines, modified design theory and methodology, and DFAM. CAD packages have also been identified as a major limitation to DFAM (Oropallo and Piegl, 2015,

Petrick and Simpson, 2013). Based fundamentally on the extrusion and removal of material, traditional CAD packages are seriously limiting the freedom of design and are still developed for educated users (Geraedts et al., 2012) requiring training and a fundamental understanding of conventional process capabilities and limitations. It is difficult to model features such as complex curved geometries which do not follow predictable mathematical geometry (Ingenia, 2013) and multi-materials (Oropallo and Piegl, 2015).

2.1.7 Process limitations

2.1.7.1 Stair-stepping

Most AM processes build parts layer by layer with each layer consisting of a cross section of finite thickness derived from the CAD data (Gausemeier et al., 2013). These layers become approximations of the original CAD data and create a stair-stepping effect that impacts the accuracy and surface finish of the final part (Hoeren and Witt, 2013, Cozmei and Caloian, 2012). The smaller the layers the closer the part will be to the intended geometry (Gibson et al., 2010b). Though this can be improved post-process (Noble et al., 2014), these additional steps will increase the processing time and is often limited to geometries which can be reached if using traditional methods (e.g. hand sanding or machining). Issues of achieving tight tolerances for moving assemblies therefore becomes paramount to ensure they work as intended (Horn and Harrysson, 2012).

2.1.7.2 Anisotropy

This layering of material also results in anisotropic mechanical properties where the bond between the layers as not as strong as within each layer (Frazier, 2014). Palanivel et al. (2016) investigated the spatially dependent properties in a Ti-6Al-4V component manufactured using powder bed fusion. They found that properties varied not only in the X (longitudinal) and Z (vertical) directions, but also from top to bottom with the bottom of the part exhibiting the best properties due to better heat dissipation from the support structures to the build base. Anisotropic characteristics were also found in material extrusion ABS parts concluding that the strength of the parts depended on the raster direction (Ahn et al., 2002).

The degree of anisotropy will vary between AM processes due to their different materials and processing methods and the impact this has on the interlayer fusion and microstructure evolution. Issues exist for multi-material printing as there is uncertainty about the behaviour of material interfaces (Gao et al., 2015) – for example between solid and flexible materials used for instant

assemblies with compliant mechanisms - and means that build orientation and part design has a big impact on the end part properties (Oropallo and Piegl, 2015).

The stair-stepping effect is also anisotropic depending on the build orientation of the part where surfaces will have different resolution depending on which axis it lies on. This means that accuracy can vary in the Z axis compared with the X and Y, which will increase as layer thickness increases. Liu (2016) explores the structural performance of consolidated AM parts compared with the assemblies considering the anisotropic nature of processes. They conclude that to improve the structural performance of consolidated assemblies, build direction and topology should be concurrently optimised. However, using PC to enhance structural performance will only work if material properties are not overly weakened.

2.1.7.3 Materials

The range of AM materials is still very limited compared with those available for conventional processes (Wong and Hernandez, 2012). Although metal alloys have been developed to address manufacturers' needs, polymers still require greater research and development and have been described in RAEng (2013) as *"the real issue and biggest opportunity for AM"* (page 14). Recent developments in photopolymers has improved the general capability of polymer AM in terms of accuracy, surface finish, and multi-material builds (Stansbury and Idacavage, 2016). However the materials are not cross-compatible with different types of processes as they rely on different material feedstocks which can greatly limited what is available to designers as the desired properties may not be achievable using the process required for the chosen material (Oropallo and Piegl, 2015).

As explored in chapter 2.1.1.1, designing material properties using meta- and biomimetic structures could mean that the range of physically different materials becomes less important than a designer's ability to design the properties they require, to be manufactured using a specific process. A perfect example of this is Schumacher et al. (2015) who achieved spatially varying elastic properties using small-scale microstructures, as opposed to Meisel et al. (2015) who used a multi-material process for achieving compliant mechanisms. Using design to achieve functional properties rather than the material could offer a solution around relatively poor mechanical properties of material jetted photopolymers, which is currently limiting most multi-material capability to prototyping applications (Wood, 2016).

Part quality can also be impacted by the characteristics of the material feedstock. As already indicated, the smaller the layer thickness the better the accuracy and surface finish. For powder based

processes the size, shape, and distribution of the powder particles can impact the flow and packing density of each layer which in turn will impact both the density and surface finish of parts (Lanzetta and Sachs, 2003, Benson and Snyders, 2015). Particles that are too small have low flowability due to high surface area so are not easy to spread in to thin layers; however particles that are too large will have high porosity reducing the strength of the final part (Vaezi and Chua, 2010).

Spath and Seitz (2013) also found that the coating mechanism impacted the layers with a rotating roller providing the most homogenous surface regardless of the size and distribution of powder particles. The resulting 'grainy' surface finish is a particular consideration for metal parts as it can impact mechanical strength due to increased crack propagation and growth. Palanivel et al. (2016) demonstrated this by testing a polished and unpolished Ti-6Al-4V component and found that polishing increased its strength. Wang and Zuo (2010) described the metal powder layer thickness as the limitation to achievable accuracy, suggesting that more work should be done on how to obtain thinner layer thickness, or even to arrange the metal particles in a string. Processes that jet material must also ensure it has low enough viscosity to be jetted, and must consider factors such as density and surface tension, and the impact of droplet size on print speed (Vaezi and Chua, 2010, Gibson et al., 2015).

2.1.7.4 Repeatability

Build consistency and repeatability within and across AM processes is a major issue in terms of both mechanical properties and accuracy (Bikas et al., 2015, Salmi et al., 2013), and is limiting wider uptake of AM for end production applications due to a lack of industry standards (Monzón et al., 2014) and robust methods for process monitoring and control (Frazier, 2014). For metal powder processes, variations in build consolidation and the presence of porosity as well as the influence of multiple thermal cycles on homogeneous microstructural evolution, results in part-to-part and spatially varying properties (Palanivel et al., 2016). Defects during the build process can be caused by a number of parameters including the material characteristics (Slotwinski and Garboczi, 2015), scanning speed, laser powder, plasma formation, grain size, and surface tension of the melt (Berumen et al., 2010).

This complex relationship between process characteristics and resulting mechanical properties has highlighted the need for in-situ process monitoring and real time closed-loop control to ensure consistent and reproducible quality (Craeghs et al., 2010, Frazier, 2014, Everton et al., 2016). Efforts are being made in research and across different standards agencies (e.g. ASTM-I F42 committee on Additive Manufacturing Technologies and ISO TC261) to develop international industry standards (Slotwinski and Moylan, 2014). These should help ensure quality, repeatability, and consistency;

reducing the risks associated with AM for end production applications and enabling wider adoption (Gao et al., 2015).

Due to building in layers, any overhanging geometry must be supported in some way whilst the material is being processed. For polymer powder bed processes (binder jetting and powder bed fusion), the support is provided by the surrounding unsintered powder. For material jetting (MJ) processes which deposit droplets of material, the jetted build material is surrounded and supported by a sacrificial gel-like or wax material which is then removed post-process. This ensures that the droplets keep their form whilst they are being solidified. Material extrusion (ME), vat polymerisation (VP), and metal powder bed fusion (MPBF) rely on support structures of the same or different material to the build material which are then broken off, machined away, or dissolved post process (Wood, 2016).

For VP and MPBF, the support structures have two important functions: supporting overhanging geometries and dissipating heat to reduce internal stresses from the high processing temperatures. This added process complexity means there are issues associated with the design and removal of supports (Atzeni and Salmi, 2012) particularly if a non-soluble support material is used which requires access by hand or tool. Reducing support material will also help reduce the amount of material used and help reduce process waste, and could impact build speed.

2.1.7.5 Speed

For most AM processes, the height of the part (i.e. the number of layers required) has the biggest impact on build time (Rickenbacher et al., 2013) due to the time required to prepare each layer. Most systems also require heat to process the material feedstock meaning they require additional cycle time to warm up and cool down the build platform before and after building. Though the development of processes such as material jetting using multiple print heads and high speed sintering (Ellis et al., 2014) has helped increase build speeds, AM still cannot yet compete with the cycle times of conventional processes (Consultants, 2013). This has an impact on both the subsequent cost and supply of parts.

Leary et al. (2014) investigated a topology optimisation method to eliminate the use of support material, resulting in a reduction of build time from 11 hours to 2.6 hours and overall material from 117.9cm to 50.9cm^3. Benson and Snyders (2015) also found that the characteristics of powder particles in AM processes can impact different process characteristics such as flow behaviour, packing density and compatibility, which then have an impact on both product quality and economics.

What these studies indicate is that the speed of AM processes is a complex relationship between multiple different parameters including the type of process, machine, part design, characteristics of the material feedstock, and processing parameters (Leary et al., 2014, Munguía et al., 2008). The post-processing currently required to overcome some of the limitations described above also have an impact of the overall manufacturing cycle time and therefore cost of AM parts. However, technological developments within both the mechanical and material elements of AM could result in ever increasing manufacturing speeds and a reduction in post-processing requirements, to the point where manufacturing cycle times could easily compete with those of traditional manufacturing processes.

2.2 Focal literature - PC

This section will be used to discuss the capabilities and benefits of achieving PC using AM processes and the potential economic implications. Though not a focus of this research, design methodologies will also be summarised to help identify a suitable redesign approach for the PC case studies.

2.2.1 Background to PC

PC is defined by Yang et al. (2015b) as *"the process […] in which multiple discrete parts are designed and fabricated together into a single part, thus reducing the number of fabricated parts and the need to join those parts together"* (page 444). PC has long been a focus of Design for Assembly (DFA) guidelines aiming to minimise the number of separate parts and improve the "*assemblability"* of the remaining parts, by answering 3 main questions defined in Boothroyd (1987) (page 3):

1. *"During the operation of the product, does this part move bodily with respect to all other parts already assembled?*
2. *For fundamental reasons, does it have to be a different material?*
3. *Does the part have to be separate from all other parts already assembled because otherwise assembly or disassembly of other separate parts cannot be carried out?"*

DFA was expanded to include Design for Manufacture (DFM) to properly consider traditional manufacturing processes during the design phase and reduce manufacturing costs (Boothroyd, 1996). Typical guidelines for DFM outlined by Prakash et al. (2014) include:

- Minimise part variations
- Attempt multi-functionality of parts
- Design for ease of fabrication
- Design with as few parts as possible
- Design parts for multiple use

Robust Design for Manufacture and Assembly (DFMA) can help to simplify products, reduce assembly and manufacturing costs, improve quality, and reduce time to market (Kuo et al., 2001). Materials and manufacturing processes account for 50-80% of the total product cost, and are determined by the design of the product (O'Driscoll, 2002).

Design for *X* (DFx) was later introduced to include the consideration of other costs such as for disassembly, service, and recycling (Kuo et al., 2001). Sodhi and Knight (1998) identified that recycling depends on the efficiency of material separation, and that the cost of disassembling small items such as fasteners far outweighed the value of the material recovered. Assembly costs can also be impacted to a greater degree by reducing part count when a manual assembly process is required compared to robotic or automatic (Boothroyd, 1987). For traditional manufacturing processes, a trade-off exists at which point the design complexity required to reduce part count and improve assembly might not outweigh increases to manufacturing costs. The resulting designs are often multiple bulky parts assembled with separate fasteners.

2.2.2 Designing for AM-enabled part consolidation

AM processes do not have the same process limitations or correlation between design complexity and manufacturing cost meaning there is no longer the same trade-off. Design for Additive Manufacturing (DFAM) methodologies has since become a major focus in research to help designers take full advantage of the capabilities of AM which often contradict rules defined for DFMA. Though the correlation between complexity and cost is considerably reduced, AM processes still have limitations which might need to be considered, such as the impact of build orientation on build time, surface finish, accuracy, and mechanical properties. Several general AM design guidelines and methods can be found in Ponche et al. (2012), Salonitis and Zarban (2015), Klahn et al. (2015), Yang and Zhao (2015), and Thompson et al. (2016).

Design methodologies focusing on PC and assemblies however are very limited. Initially Rodrigue and Rivette (2010) developed a method for consolidating and optimising existing products, but followed the original DFA rule that parts required to move relative to each other could not be consolidated. Maidin et al. (2012) identified four approaches to consolidation using AM: instant assembly features, fasteners removal features, multiple functional parts and dual material features. They developed a design feature database to support DFAM, with 32 PC related design features including living hinge, multiple link, hook clip, and snap fit features.

Yang et al. (2015b) identified that AM-enabled PC is far more effective at reducing part count than traditional DFMA and developed a method for function integration and structure optimisation. Cardona (2015) demonstrated the consolidation of a harmonic drive by using DFMA guidelines and "Principle of Fragmentation" initiated by Theory of Inventive Problem Solving to analyse the functions and best fit of parts to be consolidated.

Schmelzle et al. (2015) defined a (re)design approach for PC based on the assessment that parts moving relative to each other, requiring different materials, and assembly of other components could still be consolidated using AM – contrary to DFA rules. The layering build method can allow for operational mechanisms, embedded components, multi-material processes, and considerably more shape complexity than traditional manufacturing processes. This was backed up by Tang et al. (2016) who developed their methodology for achieving sustainable designs through functionality integration and part consolidation. Liu (2016) also defined guidelines for PC focusing on improving structural performance. An overriding theme of these methods is that consolidation should occur alongside structural and performance optimisation, often achieved using complex computational software such as Finite element analysis (FEA).

2.2.3 Examples of PC

Hague et al. (2003b) consolidated an enclosure from 3 parts to 1, and took advantage of AM's capability for organic forms for a more ergonomic design (Figure 17). Several non-assembly robotic systems utilising traditional mechanisms and embedded components have been designed and tested using AM (Mavroidis et al., 2000, De Laurentis and Mavroidis, 2004). Compliant mechanisms were used by Blanes et al. (2014) and Grzesiak et al. (2011) to design robot grippers out of one part, which also integrated pneumatic actuators and complex chassis shapes (Figure 18).



Figure 17: Redesign of a product a) original design with 3 parts b) new ergonomic design with 1 part. Images taken from Hague et al. (2003b)

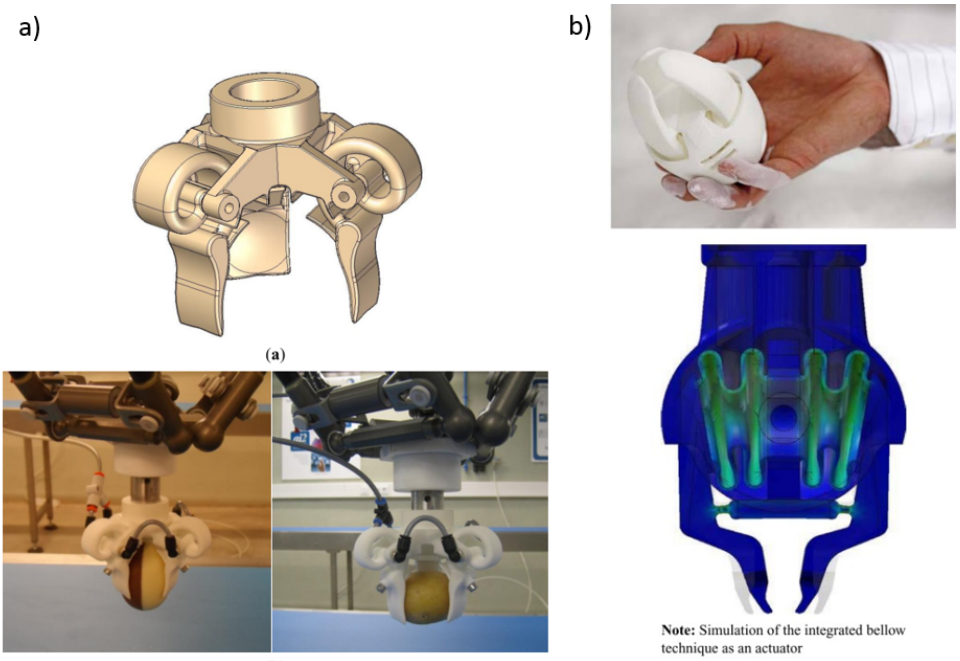


Figure 18: a) Concentric gripper with pneumatically operated traditional and compliant mechanisms for grasping foods of different shape Blanes et al. (2014) b) The bionic handling assistant made of one part with an integrated bellow technique to act as actuator. Images taken from Grzesiak et al. (2011)

Two case studies presented in Horn and Harrysson (2012) show complex mechanical assemblies consolidated into single lightweight components using operational mechanisms and lightweight mesh structures (Figure 19). Dietrich and Cudney (2011) consolidated a multiple part manifold duct sub-assembly into a single piece, investigating the impact of tolerance accumulation on quality.

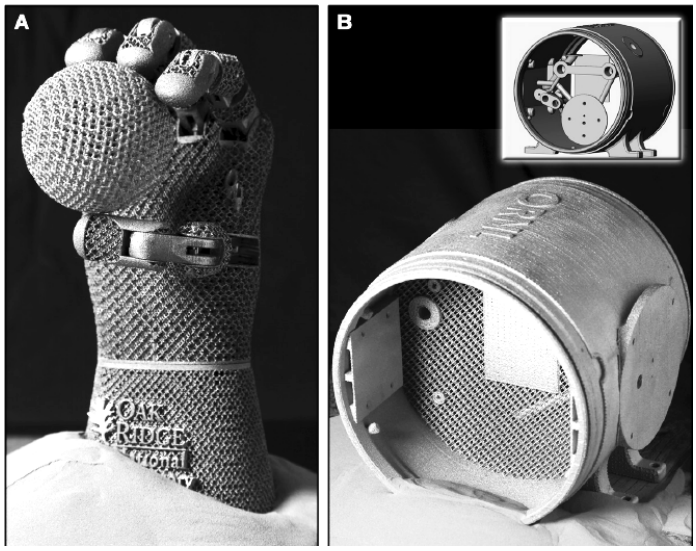


Figure 19: (A) Lightweight robotic hand utilising stochastic network structures and hydraulic and pneumatic action. (B) Underwater robotic system combining multiple parts into one compact lightweight structure. Image taken from (Horn and Harrysson, 2012)

Yang et al. (2015b) redesigned a triple clamp for a bike steering handle to reduce the number of parts from 19 to 7 and used lattice structures to achieve a 20% reduction in mass. Tang et al. (2016) explore the same case study but use topology optimisation to optimise the design from an environmental perspective instead of mass reduction (Figure 20). The limitations with this application is that separate parts were maintained to enable assembly of the bike steering handles. Applying PC design methodologies to the rest of the bike assembly could result in further significant part reduction.

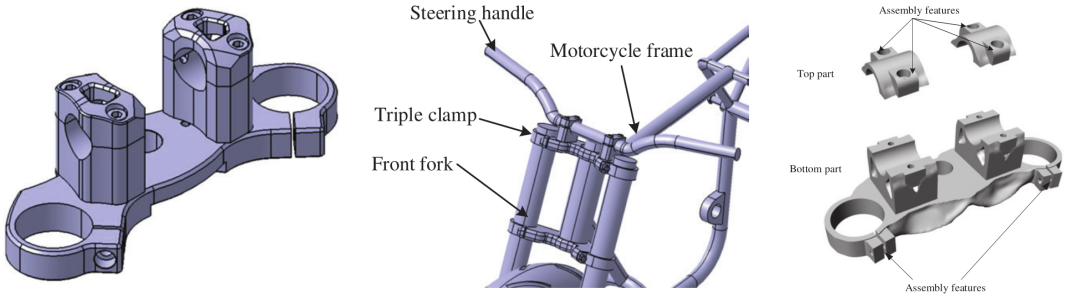


Figure 20: Original and consolidated redesign of a triple clamp for bike steering handle, reducing part count from 19 to 7. Images taken from Tang et al. (2016)

Schmelzle et al. (2015) redesigned a 17-component test equipment into 1 hydraulic manifold (Figure 21), maintaining both the original hydraulic logic and interface with other system components. The resulting design not only reduced the size and number of parts, but also reduced leakages and improved performance.

a) b)

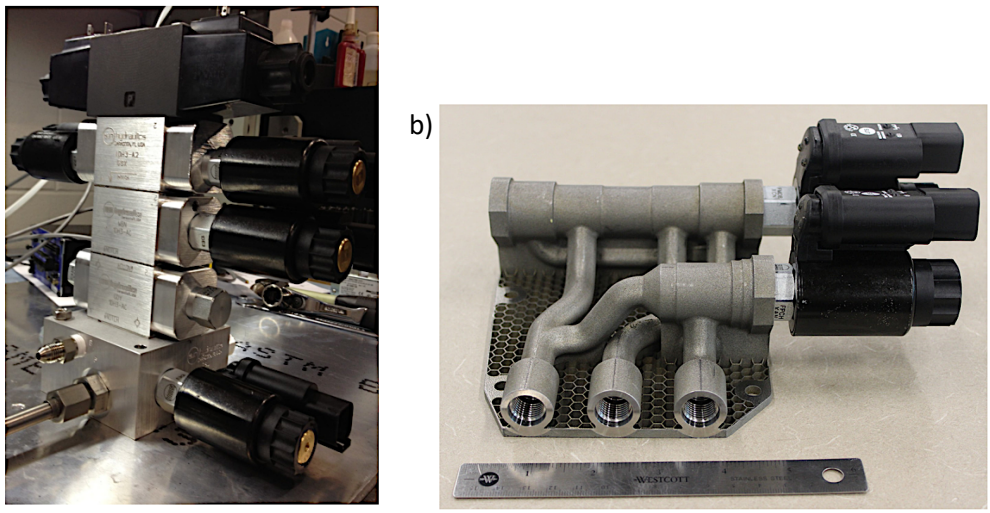


Figure 21: a) Original test equipment consisting of 17 parts and standard components b) consolidated hydraulic manifold with connectors and fittings. Images taken from Schmelzle et al. (2015)

GE Aviation used metal PBF to reduce the number of parts in a jet engine component from 18 to 1 (Figure 22), with a 25% weight reduction and more intricate cooling pathways and support ligaments resulting in five times the service life (Liu et al., 2017). The design freedom enabled by the AM process also allowed for a simpler design that reduced the number of brazed and welds from 25 to 5.

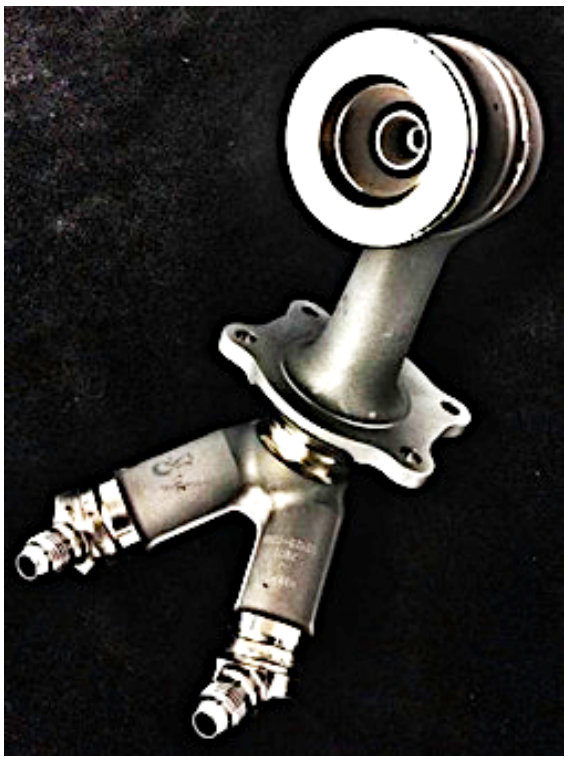


Figure 22 GE Leap Engine fuel nozzle created using direct metal laser melting via the EOS metal powder bed fusion machine. Image taken from Liu et al. (2017)

Developments in AM processes has made multi-material printing a reality which could also be used to achieve PC. Designers can then specify material properties like hardness and flexibility in place of discrete hinges (Gao et al., 2015, Gaynor et al., 2014); such as the compliant joint prototype embedded with shape memory alloy by Meisel et al. (2015). Pereira et al. (2014b) developed an automatic algorithm for defining internal fibres to route light between arbitrary surfaces within a model fabricated using multi-material printing (Figure 23). Two materials with different indices of refraction were used enabling the light to be transmitted through the model from point to point by total internal reflection. Though the focus of this application was automatic computation of 3D printed optical fibres, achieving the same functionality using traditional manufacturing processes and parts would have required a considerably more complex assembly and fibre optic cables.

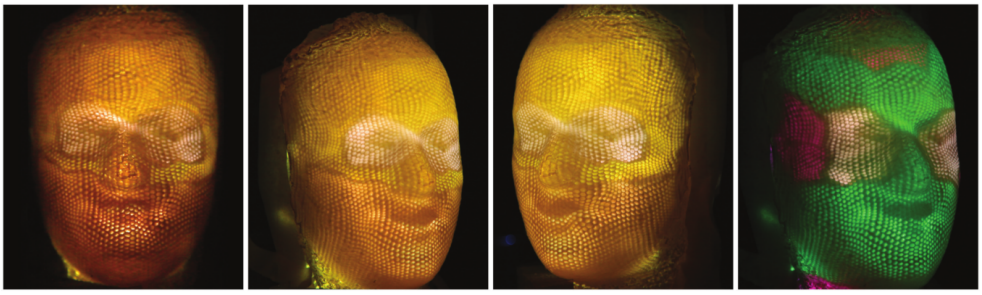


Figure 23: Multi-material printing of automatically generated fibre optic paths using two materials with different indices of refraction, transmitting light from point to point by total internal reflection. Image taken from Pereira et al. (2014a)

Even if assembly of components is still required for the function of the product, these will not necessarily require separate parts and fasteners such as would be required when using traditional manufacturing processes. Schmelzle et al. (2015) had to accommodate the interface between the consolidated hydraulic manifold and pre-existing standard components (flow control valves and military standard fittings) by transitioning from a diamond to round shaped fluid cross-section. However, secondary machining operations were still needed for all threaded surfaces required for assembly. Unlike metals, the high elasticity of polymers and the geometric freedom of polymer AM processes means complex designs for snap fit connections, positive locking with complex shapes, and elastic force connection can be designed to reduce parts needed for assemblage and fastening (Grzesiak et al., 2011, Gibson et al., 2010a).

Riss et al. (2014) combines several AM capabilities and explores load-dependent optimised honeycomb structures for a lightweight sandwich component, integrating additional functions and varying its wall thickness and diameter (Figure 24a). Functional components like threads or bearing carriers are also integrated directly into the honeycomb core and snap-in connections designed to enable assembly of multiple structures for larger applications (Figure 24b). A number of different fasteners designs were developed and tested using AM by Dressler et al. (2016) shown in Figure 25.

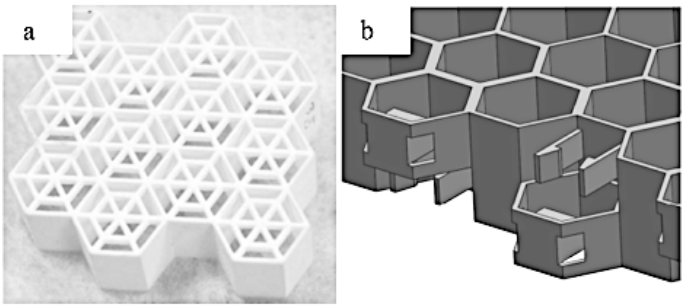


Figure 24: a) anti-telegraphing solution using hexagonal lattice structures b) honeycomb structures with snap-in connections to overcome size limitation of AM machine. Images taken from Riss et al. (2014)

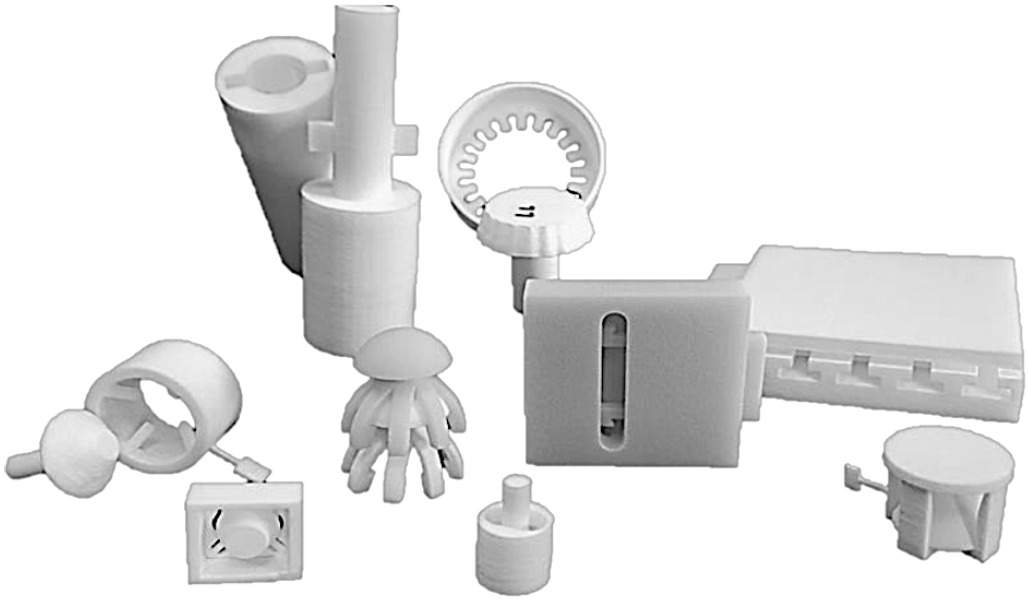


Figure 25: Fastener designs built using AM. Image taken from Dressler et al. (2016)

2.2.4 Economic implications of part consolidation

Discussions on economic implications of PC enabled by AM is limited, and has focused on reducing assembly requirements, reducing inventory and supply chain complexity, and improving product quality by reducing tolerance stack-up. Weller et al. (2015) for example mention how functional integrative designs could reduce assembly, which may reduce marginal costs for production of assembly-intensive products. Atzeni et al. (2010) and Atzeni and Salmi (2012) identified that rationalising part count can reduce assembly time and costs, and improve quality. More efficient assembly of products means more could be assembled and therefore sold, and lead times can be shortened helping reduce demand shrinkage and improve customer satisfaction (Weller et al., 2015).

Thomas (2015) discuss that screws, bolts, and intermediate assemblies might not be needed through PC helping to eliminate some inventory, transportation, and whole-sale costs and decrease risk to supply disruptions. However, they also identify that most studies look at single parts, whilst investigation into assemblies do not consider supply chain effects, with many costs hidden in the supply chain and inventory. Aliakbari (2012) discuss PC from the perspective of lean as it could eliminate sub-products and assembly processes and non-value adding operations such as transportation, whilst reducing the number of suppliers.

Oettmeier and Hofmann (2016) found significant opportunities on the supply side of operations from eliminating pre-assembly activities; reducing the number of components, suppliers, and

transportation services due to multifunctionality; and eliminating sub-assemblies. Fewer suppliers means less risk associated with fluctuating lead times (Achillas et al., 2014, Gao et al., 2015) and reduces the need for complex inventory management and logistics information systems (Khajavi et al., 2014). Dietrich and Cudney (2011) also investigated the impacts of part consolidation (integrative design) on dimensional deviation, and found that PC can help improve product quality by reducing tolerance stack-up. Ashour Pour et al. (2015) summarise the impactful dynamics of part consolidation with decentralised production as:

- Reduce warehousing, transportation, inventory
- Simplify supply chain through reduced time to market and lead time
- Reduce material, energy and natural resource use = eventually significant sustainable and economic benefits

Despite ample mention of PC and conceptual discussions of the impacts, there is very little empirical evidence provided or methods outlined to investigate and quantify lifecycle impacts (Wood, 2016, Thomas, 2015, Thomas and Gilbert, 2014). AM cost models and their ability to account for the potential impacts outlined above will be discussed in 2.3.2.1. What is not discussed is the potential impact of design freedom and PC on development efficiency. Fewer parts need to be designed, drawn, tested, reviewed, and sourced which could eliminate some development cost elements.

2.3 Focal literature – implementation of manufacturing technologies

Global competition and tightly specified customer expectations and needs have created an increasingly uncertain environment for organisations (Cozmei and Caloian, 2012). Adopting advanced manufacturing technologies (AMTs) can give firms several options to grow and enter new markets; create new products and reduce costs; increase flexibility and product quality; and provide better managerial control (Hayes and Jaikumar, 1991). However despite the capabilities and benefits enabled by AM, it is still uncommon in direct parts manufacturing (Oettmeier and Hofmann, 2016). According to Bogers et al. (2016), its hyper flexible nature means it has no real value if it is not commercialised profitably.

D'aveni (2013) suggest organisations along supply, manufacturing, and retailing chains need to choose suitable supply chain configurations and rethink their strategy and operations. Business models will need to be developed and adapted to take advantage of AM's potential, and must then be implemented correctly to increase their competitive advantage (Khajavi et al., 2014). For a better understanding of the requirements for adoption, AMT implementation research will be explored with regards to the general process and determinants for success; focusing on the pre-installation phase

and justification approach. Research specifically focusing on AM implementation will then be discussed, followed by an evaluation of AM cost models as an economic justification method to consider the cost impacts of PC during the pre-installation phase.

2.3.1 Advanced manufacturing technology implementation research

AMTs are typically modern computer-based systems that aim to improve manufacturing operations by reducing costs and increasing flexibility and quality, such as computer aided design (CAD), computer aided manufacturing (CAM), and automated stock management (Hewitt-Dundas and Ireland, 2000, Oettmeier and Hofmann, 2016, Efstathiades et al., 2002). Implementation falls between innovation and diffusion and is defined by Voss (1988) as *"the user process that leads to the successful adoption of an innovation of new technology"* (page 59). Implementation success is defined by Udo and Ehie (1996) as *"when set goals and objectives stipulated by the adoption strategy are fully realised"* (page 92), i.e. the adopting organisation achieved all their required and expected benefits.

Research into AMT implementation gained momentum when organisations were identifying that it was not delivering them with the required or expected benefits (Chen and Small, 1994), with 50-75% of AMT implementation being dubbed failures in terms of flexibility, quality, and reliability (Lewis and Boyer, 2002). Generally, the implementation process for AMTs follows Voss (1988)'s 3-phase implementation lifecycle model of 1) pre-installation, 2) installation and commissioning, and 3) post-commissioning (Figure 26). He identified that though a common view of implementation encompassed actions from purchase and installation to use, actions and conditions prior to that are important determinants of implementation success. For example, strategic and technical planning, and workforce consultation.

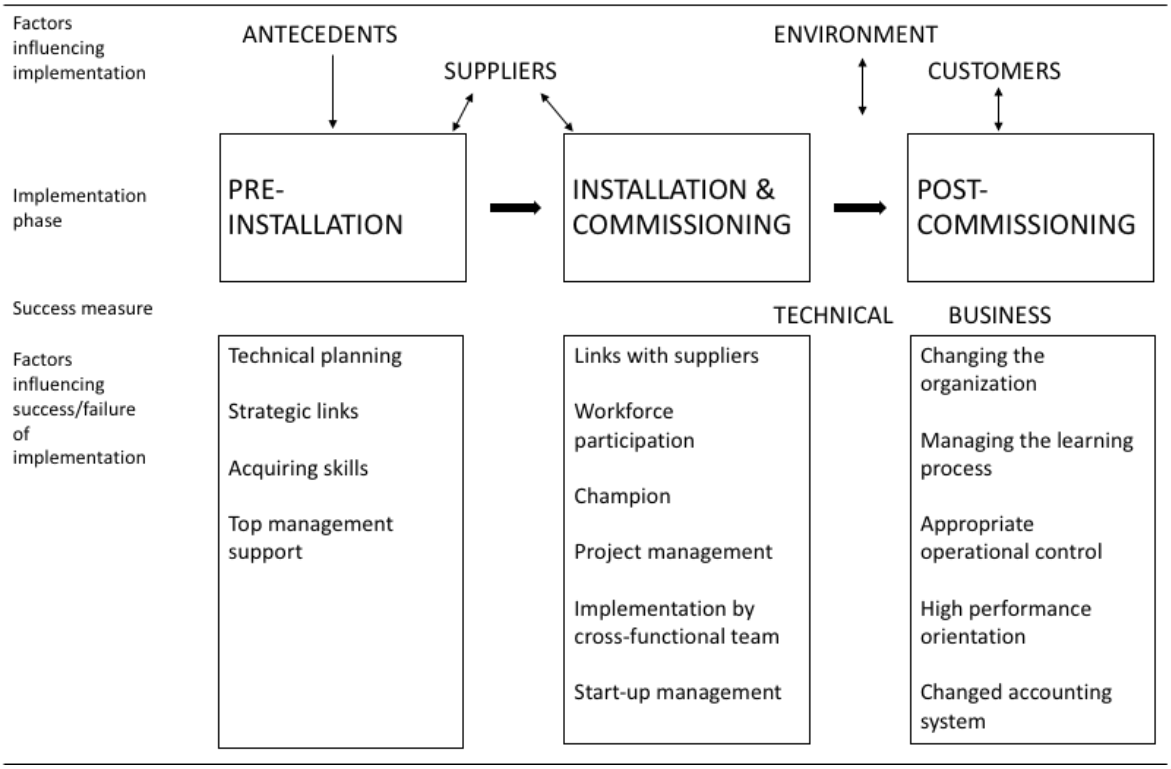


Figure 26: The process of implementation; defining pre-installation phase. Image taken from Voss (1988)

A study completed by Lewis and Boyer (2002) found that high performing plants developed a supportive fit between the capabilities of the new AMT and their culture, strategic priorities, and employee training support. They suggest that plants should create a formal fit between the AMT and their operations strategy prior to installation with training, well-defined long-term goals, clearly communicated objectives, and pilot projects. A study by Udoka and Nazemetz (1990) found there was a statistical significance between successful and unsuccessful projects in the US, with regards to activities such as formulating a strategy and aligning it with their organisation system and culture; educating employees; and top-down planning with bottom-up implementation. Saberi and Yusuff (2011) also found that improving AMT implementation performance required the technology to be supported by other factors related to the organisation structure and culture, technology, strategy, and HR and management.

These and other investigations into implementation failures found that the pre-installation phase (as defined by Voss (1988)) was the most critical for increasing success as it ensured a robust decision-making and planning process (Udoka and Nazemetz, 1990, Hayes and Jaikumar, 1991, Laosirihongthong et al., 2003, Chen and Small, 1994, Shang and Sueyoshi, 1995, Small and Yasin, 1997).

2.3.1.1 Pre-installation phase of implementation

Several planning and transfer models have since been developed to try and provide organisations with a structured approach for their pre-installation phase to improve the success of technology implementation. Chen and Small (1994) identified that though pre-installation activities are critical for success, they are not adequately addressed in Voss (1988)'s current model of implementation. They developed an integrated planning model based on the results of a cross-section survey which helped identify factors that impacted success. The model has three main phases (Figure 27): business planning and evaluation of production processes, technology monitoring, and the pre-installation phase incorporating planning and justification activities. Shang and Sueyoshi (1995) developed a framework for the selection of a flexible manufacturing system (FMS) incorporating qualitative, quantitative, and financial factors at the strategic and tactical level (Figure 28).

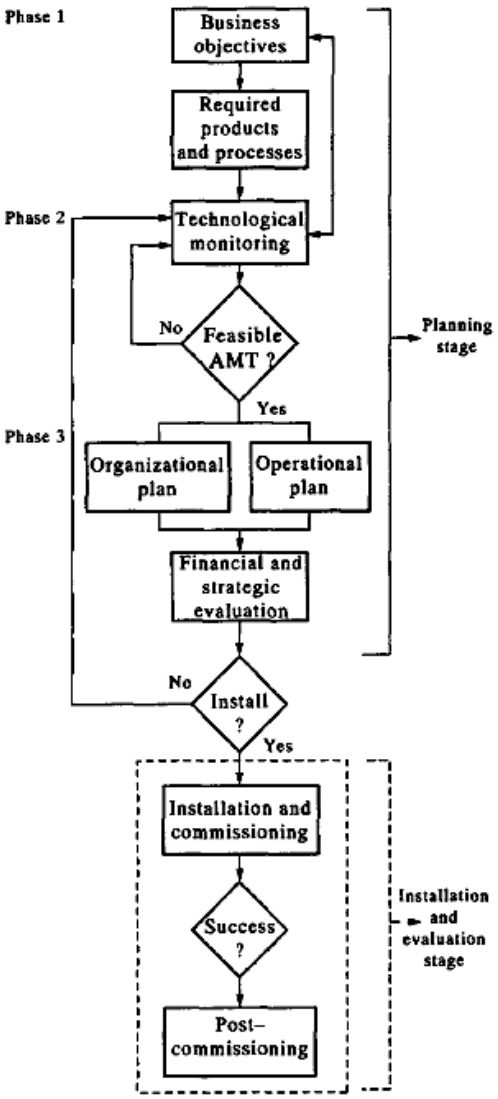


Figure 27: Integrated planning model for AMT implementation. Image taken from Chen and Small (1994)

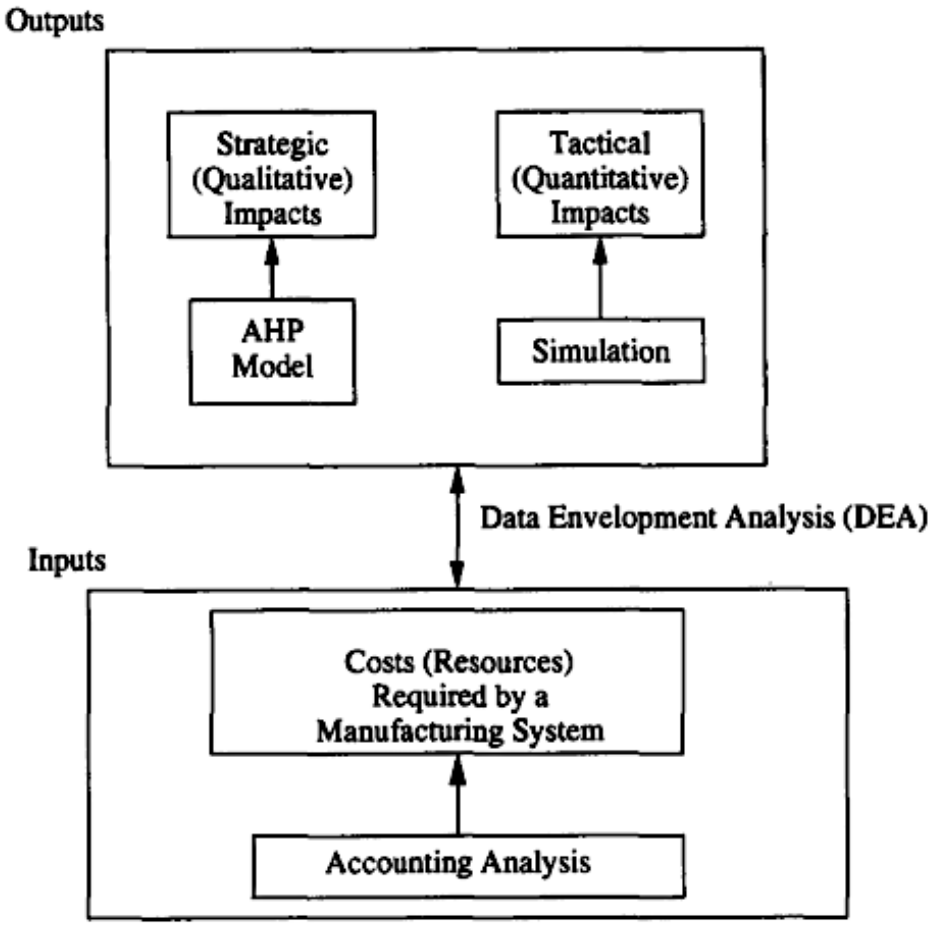


Figure 28: Framework for the selection of a flexible manufacturing system (FMS) incorporating qualitative, quantitative, and financial factors at the strategic and tactical level. Image taken from Shang and Sueyoshi (1995)

A planning and implementation framework for AMT was developed by Small and Yasin (1997) who also identified five managerial action modes covering different stages of the implementation process: examine, planning, modify, implement, and track. Efstathiades et al. (2002) used the results of a questionnaire sent to 40 companies to identify that the processes used to justify implementation (within the pre-installation phase) were the greatest impediment to success. They subsequently developed an integrated process plan for planning, transfer, and implementation of AMT to achieve technical, manufacturing, and business success. They define a strategic planning approach requiring development of an integrated business plan and matching products and markets with technology; and a defensive planning approach based on operations concerns or problems faced within manufacturing.

More recently, Saberi and Yusuff (2011) proposed a framework for determining requirements of adoption, helping to achieve benefits by aligning organisation structure and culture with strategy and

human resource and management. The framework is then summarised in a T-O-P map showing the alignment of performance, organisation, and technology (Figure 29).

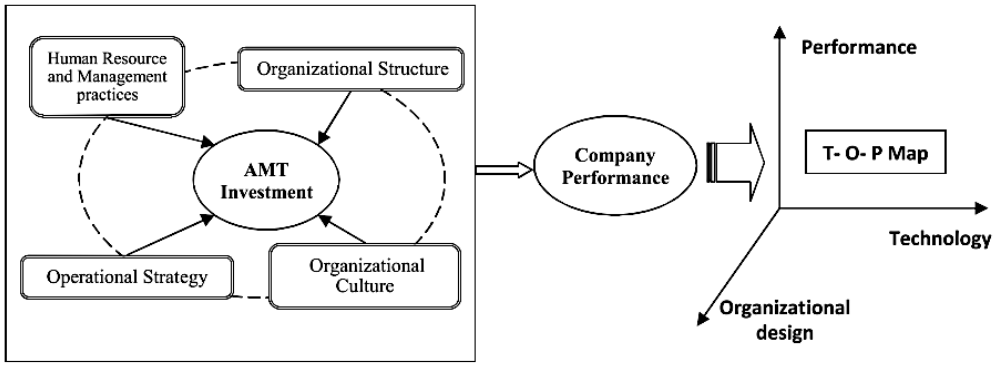


Figure 29: Framework for determining requirements for adoption summarised in a T-O-P map showing alignment of performance, technology and organisation. Image taken from Saberi and Yusuff (2011)

Drawing from the research above, a general implementation process structure has been identified by the researcher with three main stages within the pre-installation phase: evaluation, justification, and planning (Figure 30). The initial evaluation process is to ensure the adopting organisation properly understands the potential impact of the technology on their organisation, and of their organisation on the implementation and use of the new technology (Small and Yasin, 1997). The next stage is to quantify the potential benefits unique to the adopting organisation (defined in the initial evaluation stage) to justify implementation (e.g. investment in machinery), ensuring a robust decision-making process and enabling critical performance measures to be set (Small and Chen, 1995, Small, 2006, Banakar and Tahriri, 2010).

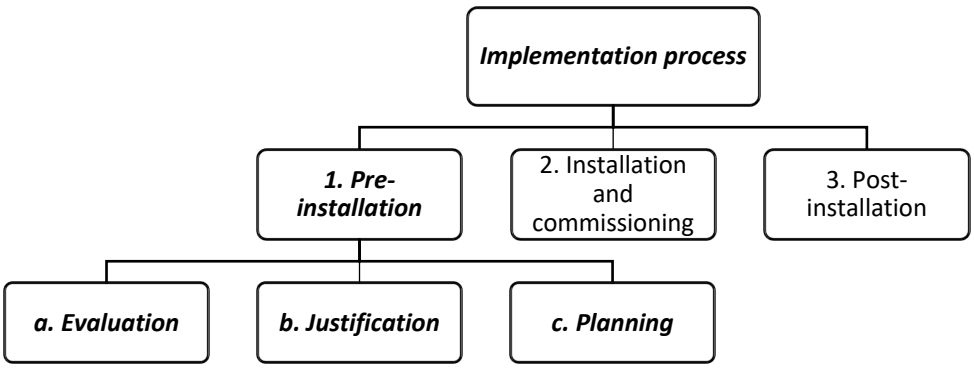


Figure 30: Implementation process structure based on advanced manufacturing technology research (own work)

Once implementation has been justified, an implementation plan can be developed to ensure alignment of the technology with organisational characteristics, and develop an integrated business plan to meet strategic objectives (Small and Yasin, 1997, Efstathiades et al., 2002). The performance measures set during the justification process can be used to ensure implementation is on track and delivering the required benefits. If not, organisations may need to adapt their plan or re-evaluate the technology-organisation relationship. Subsequent research into the pre-installation phase has focused on justification due to the difficulty of quantifying both tangible (objective and easily quantifiable) and intangible (subjective and fuzzy) benefits of AMT implementation (Small and Chen, 1995, Aravindan and Punniyamoorthy, 2002, Borges and Tan, 2007, Kreng et al., 2011).

2.3.1.2 Justifying advanced manufacturing technology implementation - approaches and methodology

Advanced manufacturing technologies (AMTs) can have a considerable benefit on the parameters of competitive advantage: speed (response time), dependability, quality, flexibility, and cost (Kakati, 1997) enabling organisations to create new products, enter new markets, and provide better managerial control (Efstathiades et al., 2002). The benefits of AMT have been identified as being both tangible (i.e. objective and easily quantifiable) such as cost and time; and intangible (subjective and difficult to quantify) such as flexibility, product quality, work conditions, learning, and response to customer demand (Small and Chen, 1995, Udo and Ehie, 1996, Banakar and Tahriri, 2010, Aravindan and Punniyamoorthy, 2002, Kreng et al., 2011, Borges and Tan, 2007). Raafat (2002) identified that improvements which are hard to quantify make it *"difficult to articulate and translate "gut" feeling into the language of finance and accounting which is a prerequisite to the funding and allocations of resources"* (page 197).

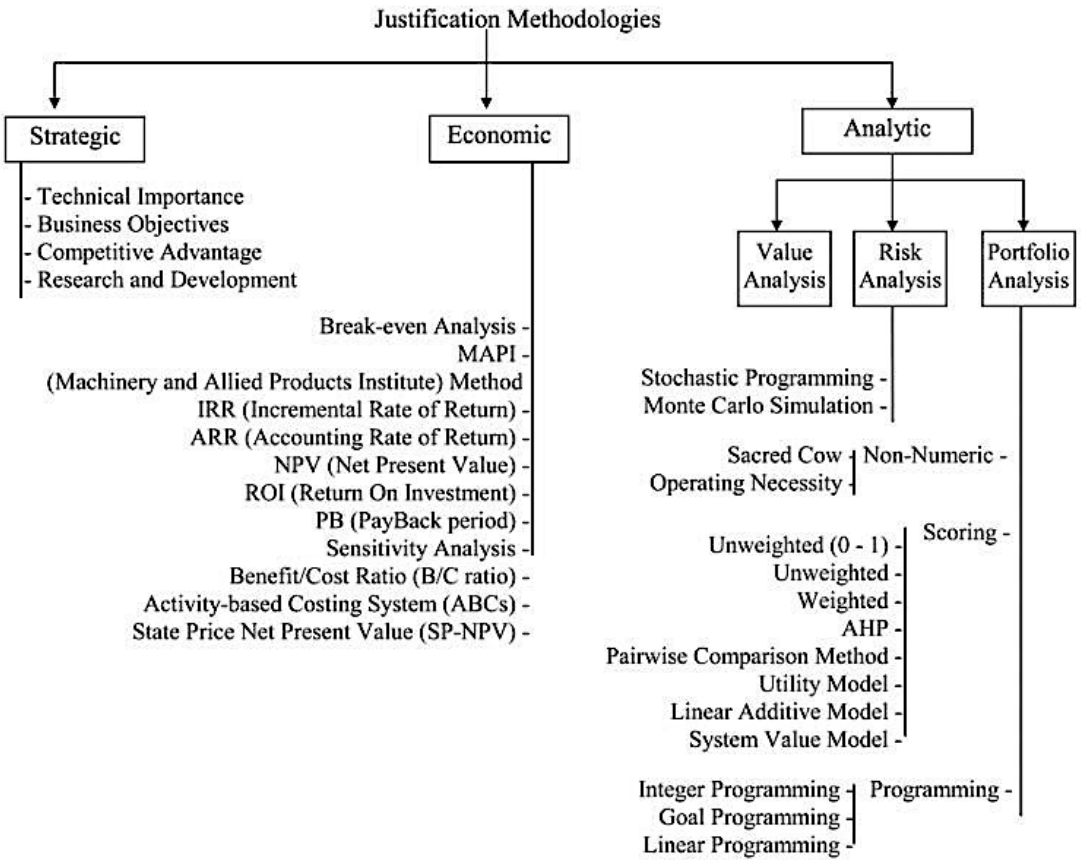


Figure 31: AMT implementation justification methodologies. Image taken from Chan et al. (2001)

Methods for justifying AMT implementation have been developed and classified into three main groups: economic, strategic, and analytic. Strategic justification approaches are primarily focused on factors such as technical importance, business objectives, competitive advantage, and R&D; whilst economic are concerned with simple financial factors such a payback and return on investment (Chan et al., 2001). Analytic methods are more complicated than economic as they can take uncertainty and multiple measures into consideration, making analyses more realistic; but can only be used when enough data on AMT impacts and performance can be gathered (Chan et al., 2001). A summary of justification methods and techniques can be found in Ertugrul Karsak and Tolga (2001), Chan et al. (2001) (Figure 31), and Banakar and Tahriri (2010) (Table 2).

Table 2 Advantages and disadvantages of economic, strategic, and analytic justification techniques. Table taken from Banakar and Tahriri (2010)

	Techniques	***Advantages***	***Disadvantages***
Economic	Payback method Return on investment Discount cash flow techniques	Ease of data collection Intuitive appeal	Do not take into account strategic and non-economic benefits Consider a single objective of cash flows, and ignore other benefits such as quality and flexibility
Strategic	Technical performance Business objectives Competitive advantage Research and development	Require less technical data	Necessity to use these techniques with economic or analytic ones since they consider long-term intangible benefits
		Use the general objectives of the firm	
Analytic	Scoring models (Analytic Hierarchy Process AHP) Mathematical programming	Uncertainty of the future and multi-objectivity can be incorporated	Require more data
	Integer programming Goal programming Data Envelopment Analysis (DEA) Stochastic methods Fuzzy set theory	Subjective criteria can be introduced in the modelling phase	Usually more complex than the economic analysis

Ertugrul Karsak and Tolga (2001) suggested intangible benefits should be examined in terms of a comprehensive evaluation of costs, as well as potential enhancement of long-term business competitiveness. This means that a hybrid justification approach using strategic with economic or analytic methods is needed (Small and Chen, 1995, Small, 2006, Banakar and Tahriri, 2010, Chan et al., 2001, Borges and Tan, 2007, Kreng et al., 2011, Aravindan and Punniyamoorthy, 2002). Regardless of the combination of methods, techniques, or approaches used to justify implementation, it will require organisations to define all tangible and intangible benefits of the technology, and quantify those impacts in terms of cost where possible.

2.3.2 AM implementation and evaluation frameworks

It is clear from the research above that a structured approach is required to help organisations successfully implement a new advanced manufacturing technology, with a robust pre-installation phase utilising a hybrid justification approach. When considering the capabilities and benefits enabled by AM processes, the potential benefits are complex interactions between design and the supply chain, with implications on business models and the value chain. Some implementation frameworks for implementing and evaluating AM have been developed, though research focusing on this area is limited.

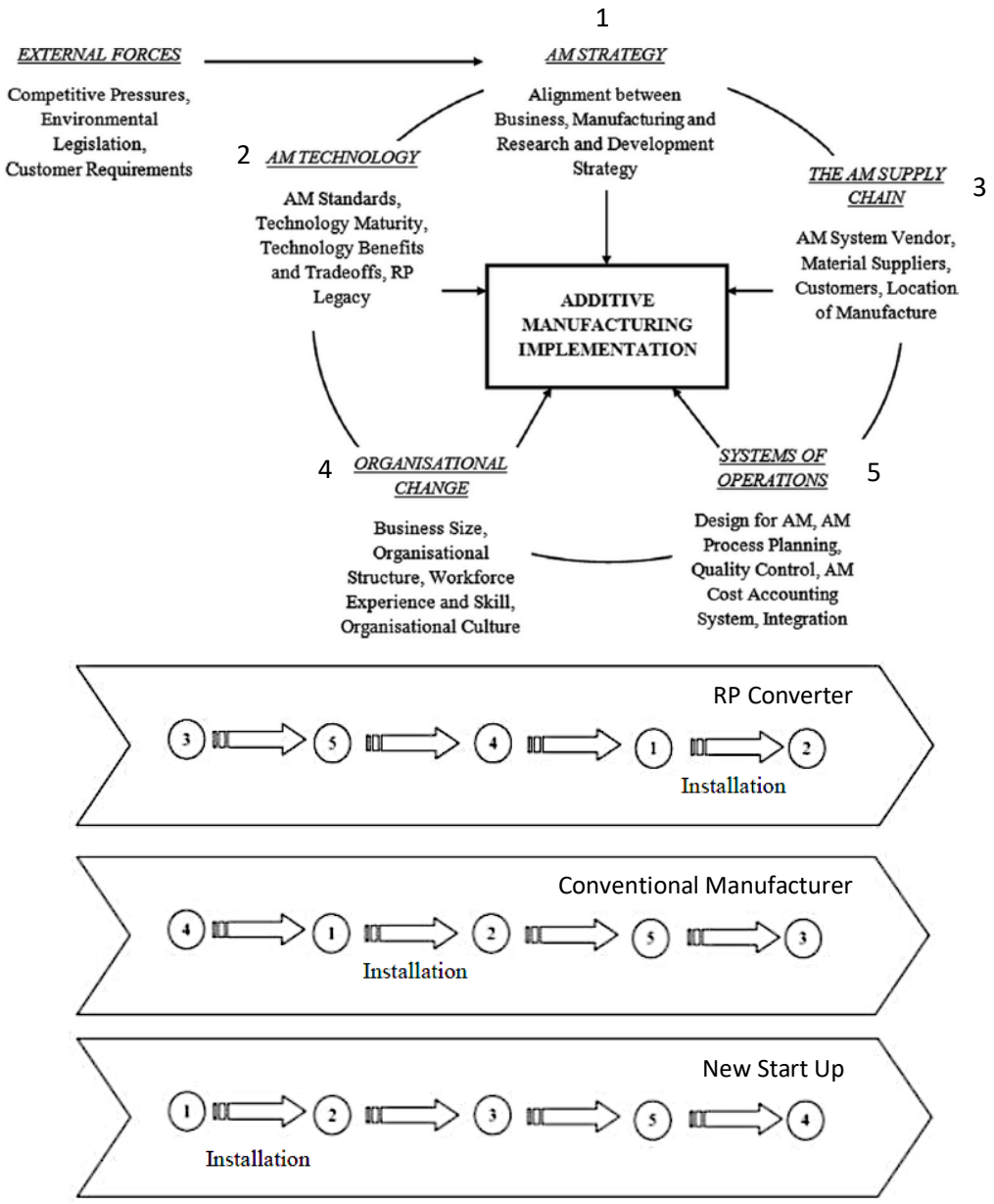


Figure 32: AM implementation framework, and the order that different companies should follow the framework depending on whether they are an RP converter, convdntioanl manufacturer, or new start-up. Images taken from Mellor et al. (2014)

Mellor et al. (2014) developed a framework based on a study of the implementation process adopted by three companies at different stages of implementation using various technologies for production parts; ranging from large multinationals to micro SMEs. The framework considers 5 main factors: AM strategy, technology, supply chain, organisational change, and systems of operations; which they suggest should be considered in different orders depending on the type of company (Figure 32). In this study, the companies were defined as a conventional manufacturer, RP converter, and new start-up. As opposed to AMT implementation research, there is no definition of a pre-installation phase,

and particularly how companies justify implementing the technology. The "AM strategy" element of the framework does imply similar considerations of pre-installation for aligning the technology with the organisation, but is then specified at different stages of implementation depending on the company; directly contradicting this as being a pre-installation activity.

Deradjat and Minshall (2015) based their framework on AMT implementation research and include Voss (1988)'s three phases as well as corporate strategy, technological, operational, organisational, and external factors (Figure 33). However, it was developed specifically based on and for the dental industry to help implement AM for mass customisation, implying again that the impacts of AM have already been evaluated, and the company has justified their business case for mass customisation. Neither framework properly considers the questions that organisations outside of a proven AM industry or application would need to ask when looking to implement AM; for example, with regards to suitable applications, impacts of technological benefits and limitations, and how to assess the benefits of different AM-enabled business models on their own competitive advantage.

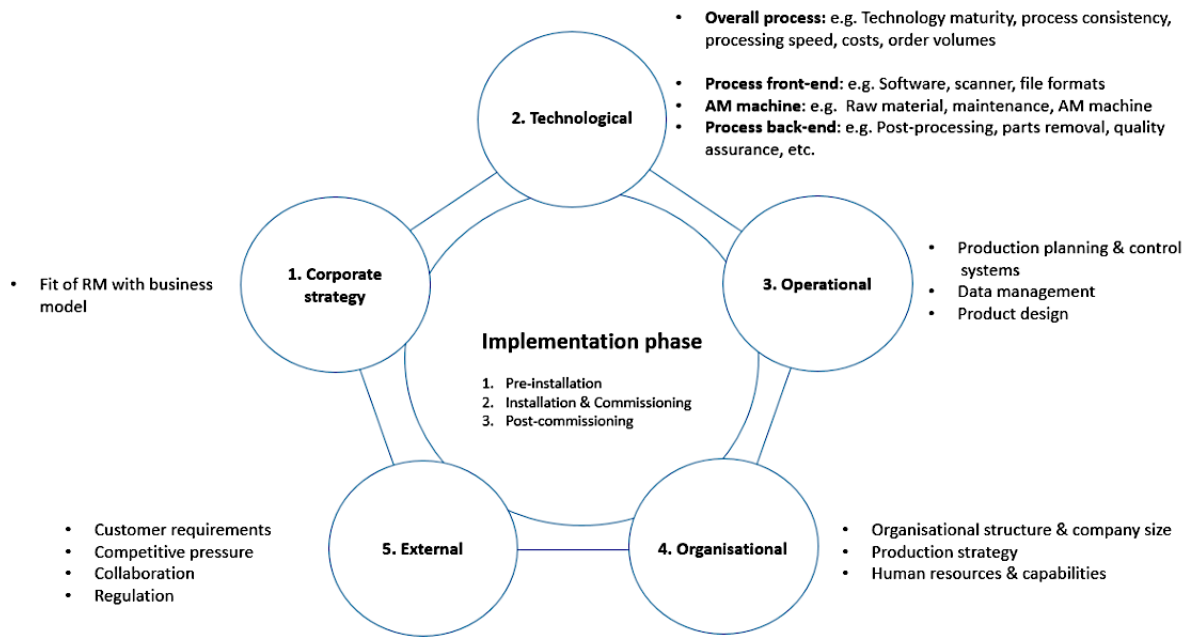


Figure 33: AM implementation framework including a pre-installation phase, but developed based on and for achieving mass customisation within the dental industry. Image taken from Deradjat and Minshall (2015)

Bianchi and Åhlström (2014) mapped the results of *"a discussion of the implications of AM on innovation and operations management"* on to a conceptual framework for the management of AM. It is based on identifying the main features of AM and what managerial practices might be required to

achieve improvements in operational performance. Their discussion also showed that the pros and cons of AM compared with traditional technologies depends on the type of product application.

Oettmeier and Hofmann (2016) identified eight factors that impact adoption decisions relating to technology, firm, market structure, and supply chain (Figure 34). Their analysis focused on supply chain-related factors as these impacted both the supply- and demand-side of operations. The supply-side benefits include small lot sizes, outsourcing of product design and production, and vertical integration of supply chains by reducing the number of components. Based on the responses from 195 firms, they found the demand-side benefits (agility and customisation) were the main determinants of AM adoption. However, these responses depended on the existing knowledge of the firm on the lifecycle benefits of AM. With regards to PC, decisions could have been made with incomplete information without a proper understanding of lifecycle economic implications, meaning responses would not properly reflect how beneficial PC could be. Supply-side benefits may also be more relevant for organisations with high product and production complexity.

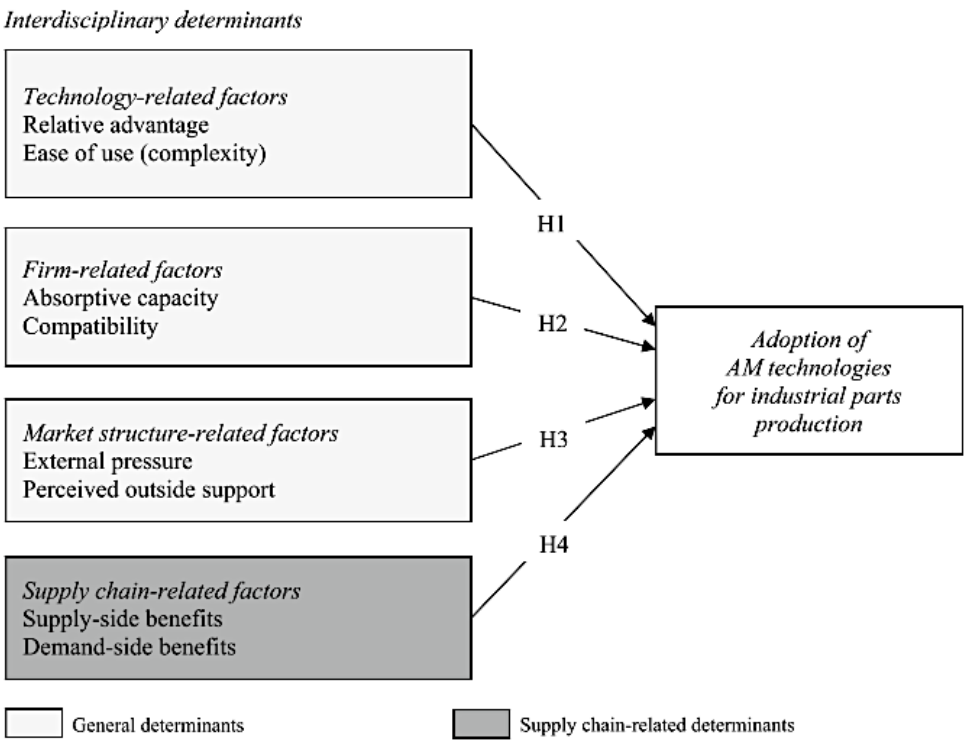


Figure 34: Conceptual model of the interdisciplinary determinants of AM technology adoption, helping provide organisations with important framework of factors which might impact adoption and implementation decisions. Image taken from Oettmeier and Hofmann (2016)

Though not specifically described as a tool within AM implementation, a few frameworks have been developed to try and facilitate decisions within product development and identify suitable applications. Conner et al. (2014) developed a reference system based on complexity, customisation, and production volumes. They concluded that suitability increases with complexity, and that an in-depth cost analysis should be performed if the intended application isn't highly complex or customised.

Ashour Pour et al. (2015) proposed a framework based on three stages: identifying suitable products, selecting a suitable machine, and performing economic assessments to compare different AM techniques to conventional processes in terms of costs (Figure 35). Though a starting point, both these frameworks are limited as they are based on assessing existing parts and products, which may have already been subject to significant compromise due to manufacturing and supply chain limitations. There is also no scope for considering intangible benefits of designing for AM, or for identifying suitable applications based on assemblies or dictated by the required functional application rather than an existing design.

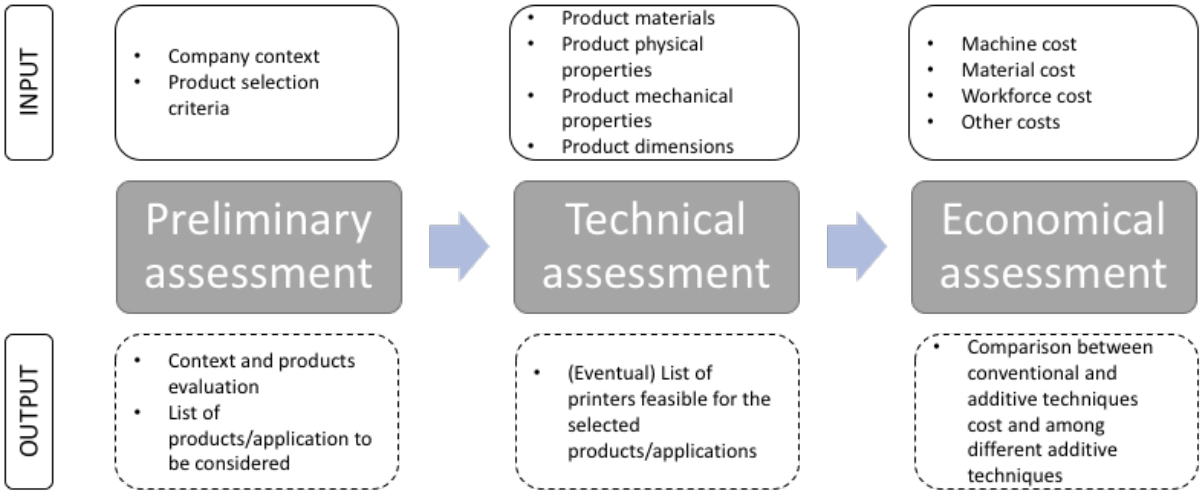


Figure 35: Proposed AM evaluation framework with economic assessment. Image taken from Ashour Pour et al. (2015)

2.3.2.1 AM cost models

Economic justification techniques for quantifying tangible impacts are a crucial part of justifying new technology implementation. With conventional manufacturing processes, complexity leads to increased costs due to longer operation times, more processing steps and the potential need for additional tooling and fixtures (Conner et al., 2014). AM processes differ significantly in their build method, meaning new process cost models have had to be developed to calculate the manufacturing

costs. The capabilities of AM also enable changes to business models with economic implications throughout a products lifecycle and throughout the value chain. Currently, most have been developed to compare AM processes to traditional processes, and identify strategies for process and product cost optimisation (Thompson et al., 2016). An overview of cost models can be found in Rickenbacher et al. (2013).

AM costs have been discussed in terms of both an opportunity and a limitation. On the one hand, they do not require high up-front costs associated with tooling and fixtures making them ideal for one-off and low volume production. On the other hand, they have a high machine and material cost associated to them, labour intensive pre- and post-processing requirements, and a small build volume and slow build speed which reduces machine productivity (Bhattacharjya et al., 2014, Oettmeier and Hofmann, 2016, Berman, 2012, Khajavi et al., 2014, Weller et al., 2015). Thermoplastics for AM processes for example can cost 10 to 100 times more than those for injection moulding (Berman, 2012). Khajavi et al. (2014) investigated the cost-effectiveness of decentralised production of spare parts using AM in the aerospace industry – but found that high machine costs only made AM cost-effective for centralised production.

Investigations found that AM processes do have some economy of scale related to build saturation for improving machine utilisation and productivity (Ruffo et al., 2006, Ashour Pour et al., 2015, Lindemann et al., 2013, Baumers et al., 2011, Rickenbacher et al., 2013, Baumers et al., 2016). Filling the build volume does not need to be done using the same part, but can use multiple, potentially unrelated parts (Ruffo and Hague, 2007).

Generally, AM is only considered cost-effective for one-off and small volume production. However, there are two potential issues with this conclusion: the first is that AM costs depend on build saturation and build time which in turn is defined by the design (size and shape) of the part/s being built, type of process, and process parameters (Leary et al., 2014, Munguía et al., 2008). This means that the volumes at which AM is no longer cost-effective compared to traditional processes can differ significantly. The second is that the cost models generally focus on well-structured costs within the manufacturing process itself, and do not account for any impacts of AM in other stages of a product's lifecycle (Thomas and Gilbert, 2014, Thompson et al., 2016). Most studies also focus on single parts not assemblies (Thomas, 2015), meaning the potential lifecycle impacts of PC on costs are not being captured.

Lindemann et al. (2012) identified that information about major cost drivers within AM was weak making it difficult to justify its use. To try and overcome these issues, they began defining a lifecycle cost structure and rating the cost drivers associated with metal AM. This was developed by Lindemann

et al. (2013) into an activity-based costing model based on the intrinsic product lifecycle to compare traditionally and additively manufactured parts within the aerospace industry. They found that the largest contributors to lifecycle costs were from the design, and usage and maintenance phases. However, a significant part of the design cost was due to design optimisation, and the research represented theoretical aspects without properly accounting for PC.

Others have tried to account for ill-structured costs such as build failures (Baumers and Holweg, 2016) and energy consumption (BAUMERS M., 2011). More relevant to PC is Atzeni et al. (2010) and Atzeni and Salmi (2012) who included assembly time within their cost models for a selective laser sintered and direct metal laser sintered consolidated assembly. They found that the breakeven point compared to traditional processes was 87,000 pieces and 42 pieces respectively. Machine and material remained the main costs drivers over assembly and machine operator costs. However, the case studies used in their research featured relatively simple 3-part assemblies.

As discussed by Weller et al. (2015); *"reduction of assembly work … may reduce marginal costs for production of assembly-intensive products"* (page 54). Therefore, organisations with products requiring more assemblage will likely see a greater impact on assembly costs through PC. However, empirical evidence and tangible data is severely lacking related to the lifecycle impacts of AM on costs. As economic justification techniques are a critical part of justifying new technology implementation, this lack of understanding around AM could be significantly impacting adoption decisions. PC, a major benefit of AM, is not being appropriately or systematically considered, but could have a major impact on costs. Existing AM process cost models will remain integral to the decision-making process within the pre-installation phase of implementation, such as to evaluate make-or-buy decisions.

2.4 Summary

As discussed, whilst the host company did not dictate the research focus or scope, the nature of their products made it clear that understanding the lifecycle impacts of PC and quantifying those in terms of a cost saving would be crucial to providing the justification that might be required for adoption. The purpose of this literature review was to gather background information and knowledge related to the three research sub-questions defined in section 1.1:

1. Are there existing methods to help organisations successfully implement AM?
2. What are the potential impacts of PC?
3. How do organisations quantify the impacts of PC to help justify AM implementation?

AMT implementation research has identified that the pre-installation phase within the implementation process is the key determinant for success. Part of this phase is a robust justification approach utilising economic, strategic, and analytic techniques to help quantify all the potential benefits from a technology for a robust decision-making and planning process. However, the pre-installation phase has not been properly defined within AM implementation frameworks which assume the business case has already been evaluated and justified.

AM's main benefits come from layer by layer build method without the need for tooling. This means it is capable of almost unlimited complexity, economic one-off and low volume production, on-demand decentralised production, co-design and prosuming, and enabling new business models with impacts throughout the value chain. A consequence of the design freedom is the ability to consolidate components far beyond what traditional manufacturing processes are capable of, for example through operational mechanisms. The benefits of PC have been discussed from the perspective of reducing assembly work, number of suppliers, and supply chain complexity; and improving product quality from tolerance stack-up. However, there is very little empirical evidence provided or consensus between researchers making it difficult to appreciate the full product lifecycle benefits of PC.

Whilst AM cost models are an important part of the economic evaluation and justification process, they currently do not systematically account for the lifecycle impacts of PC. The true benefits and costs of adopting AM is therefore only partially understood. This means there is currently no systematic approach existed for organisations to quantify the potential impacts of PC on costs during the pre-installation phase, impacting overall adoption and implementation success. The main literature gaps identified within this review can be summarised as follows:

i. Application of AMT pre-installation principles to AM adoption
ii. Ability of current AM cost models to quantify benefits of PC

The problems faced by organisations looking to adopt and implement AM in industry has been summarised by other researchers:

"The use of AM is still rather uncommon, especially in direct part manufacturing. Reasons for firms' hesitant adoption … include difficulties in management and implementation [and] *insecurity about the how, where and why to employ additive technologies. This implies that more efforts need to be taken to foster understanding about the factors, which affect the decision to pursue AM"*

(Oettmeier and Hofmann, 2016; page 3)

[There is] *"very little research … on the methods to integrate this new manufacturing technology in industry"*

(Geraedts et al., 2012)

"Scarce available literature is not in line with companies' requirements. They are focusing mostly on technological aspects, and do not provide a holistic view to ensure the evaluation of all the benefits and limitation is AM"

(Ashour Pour et al., 2015; page 146)

[It is] *"difficult to articulate and translate "gut" feeling into the language of finance and accounting which is a prerequisite to the funding and allocations of resources"*

(Raafat, 2002; page 197)

3 Methodology

3.1 Introduction

The purpose of the PC cost model was to enable organisations to quantify the potential impact of PC on costs during their pre-installation phase of implementation. This could then be used to help justify AM adoption based on the potential benefits of PC, and enable a robust decision-making and planning process. The research was part-sponsored by and based in MIL (referred to as the *host company* throughout this research), who design and assemble precision instruments for material and biophysical characterisation.

Section 3.1.1 presents the background and justification for using a case study research approach which was the overall methodology followed in this research. It is important to note that this research was part-sponsored by the host company, which limited the researcher from using data from other companies to validate the cost model. The host company is therefore treated as a single company case study. PC redesign case studies used to provide empirical evidence with regards to an achievable reduction in part count are treated as the sub-units.

The next section presents the methodology followed to develop the PC cost model. First, the elements of the model are defined in section 3.2.1 based on activities within the host company that might be impacted by the number of parts within an assembly. The PC cost model equation is then developed, which first required important terms to be defined in section 3.2.2 to accurately reflect an impact from part count reduction. Then the cost elements were defined as a direct cost or cost rate in section 3.2.3 depending on the nature of that activity, enabling an equation to be defined to calculate the difference in cost between a consolidated and unconsolidated assembly.

The cost model is then trialled on the host company by defining the cost and time parameters using data from the host company, and the number of *Units* (number of parts) in an unconsolidated and consolidated sub-assembly using the embedded redesign case studies (sub-units). The redesign case studies and redesign approach followed by the researcher is defined in section 3.3.1. The different analyses to be performed are then summarised in section 3.3.2. The method for improving utilisation of the cost model is covered in section 3.3.3.

The overall methodology for developing and trialling the PC cost model can be split into three main steps, with three sub-steps for trialling the model, displayed graphically in Figure 36:

1. **Define the cost elements** impacted by PC based on literature and *Development* and *Production* activities of the host company

2. **Develop the PC cost model** equation to quantify the impacts of PC on costs
3. **Trial the model on the host company** using results from the redesign case studies and company-defined data
    a. ***Identify the potential for PC*** within host company products using a range of PC redesign case studies
    b. Define analyses to be performed
    c. Improve utilisation of the cost model

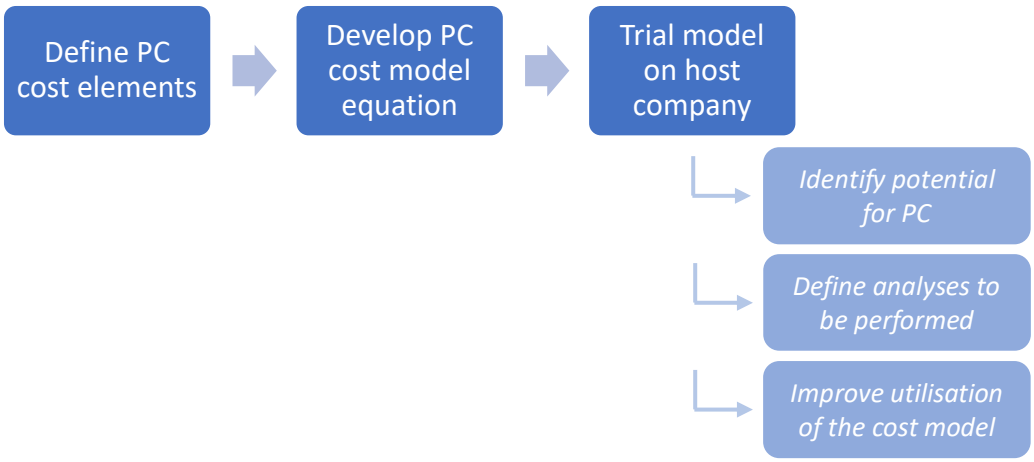


Figure 36: Research methodology followed to deliver research objectives

3.1.1 Research methodology - Case study research

Case study research methodology is an empirical approach to developing an understanding of "real world" events (McCutcheon and Meredith, 1993). As explained by Noor (2008), "*the choice of which research method to employ is dependent upon the nature of the research problem"* and *"case study is not intended as a study of the entire organisation, rather is intended to focus on a particular issue, feature, or unit of analysis"* (page 1602). Although there is no single accepted definition of case study research, according to Benbasat et al. (1987) *"a case study examines a phenomenon in its natural setting, employing multiple methods of data collection to gather information from one or a few entities"* (page 370).

Yin (2011) identified that case studies are important when research addresses either a descriptive question, or an explanatory question. Four main instances to consider case study research were defined by Yin (2013) as:

a) The focus of the study is to answer "how" and "why" questions

b) You cannot manipulate the behaviour of those involved in the study
c) You want to cover contextual conditions because you believe they are relevant to the phenomenon under study
d) The boundaries are not clear between the phenomenon and context

Mellor (2014) matches four research purposes (theory exploration, theory building, theory testing, and theory refinement/extension) with suitable research methodology shown in Table 3. Per these definitions, a case study research method is ideal for answering the main research question defined in this thesis. The question is explanatory in nature seeking to understand the relationship between multiple phenomena and the implications of contextual conditions. The purpose of this research can be categorised as exploration, theory building, and theory testing.

Table 3 matching research purpose with methodology. Table taken from Mellor (2014)

Purpose	**Research question**	**Research structure**
Exploration Uncover areas for research and theory development	Is there something interesting enough to justify research?	In-depth case studies Unfocused, longitudinal field study
Theory building Identify/describe key variables Identify linkages between variable Identify "why" these relationships exist	What are the key variables? What are the patterns or linkages between variables? Why should these relationships exist?	Few focused case studies In-depth field studies Multi-site case studies Best-in-class case studies
Theory testing Test the theories developed in the previous stages Predict future outcomes	Are the theories we have generated able to survive the test of empirical data? Did we get the behaviour that was predicted by the theory or did we observe another unanticipated behaviour?	Experiment Quasi-experiment Multiple case studies Large-scale sample of population
Theory extension/refinement To better structure the theories in light of the observed results	How generalisable is the theory? Where does the theory apply?	Experiment Quasi-experiment Case studies Large-scale sample of population

Initially, the background theory and literature is explored to identify literature gaps and a suitable research focus. In this case, there has been no combination of AMT implementation research with the cost impacts of PC for AM adoption. This theory is then built upon by developing a cost model based on the host company. The theory is then tested by trialling the cost model on the host company, to understand a specific instance of the significance of the cost impact of PC within AM adoption. With regards to theory extension/refinement, though the model is trialled on the host company and

developed to be adaptable to other organisations, it has not been tested across different "cases" or "instances", i.e. by other adopting organisations.

According to Baxter and Jack (2008), after identifying whether case study research is suitable, the next steps in case study design are determining the case/unit of analysis, building the case and placing boundaries to maintain reasonable scope, and determining the type of case study. The "case" or "unit" in this research is the cost impact of PC based on a part count reduction. Boundaries are defined for this research within the definition of the cost elements in terms of limiting the product lifecycle stages being investigated, and the exclusion of ill-structured costs.

It is also important to identify whether single or multiple case studies is most suitable (Benbasat et al., 1987). This research can be characterised as a single company case study with embedded units/cases ("*subunits"*). Only the host company features as a case for the overall research question as the funding of this research did not enable other companies to be investigated. The PC redesign case studies are the subunits to provide empirical evidence with regards to a realistic reduction in part count. They also help provide a means to investigate PC in isolation in terms of design approach and freedom, but have not been optimised from a cost or functional perspective. According to Baxter and Jack (2008), single case studies with embedded units "*serve to better illuminate the case"*, but conclude that *"researchers must return to the global issues they initially set out to address"* (page 550).

With regards to the research presented in this thesis, whilst the PC redesign case studies show what/how part count reduction can be achieved for the host company, the researcher must return to the original research question and objectives relating to the significance of the cost impact of PC within AM adoption.

Flyvbjerg (2006) identify five common misunderstandings that exist about case study research:

1. *Theoretical knowledge is more valuable than practical knowledge*
2. *One cannot generalize from a single case, therefore, the single-case study cannot contribute to scientific development*
3. *The case study is most useful for generating hypotheses, whereas other methods are more suitable for hypotheses testing and theory building*
4. *The case study contains a bias toward verification*
5. *It is often difficult to summarize specific case studies*

They explain and correct these five common misunderstandings and conclude that *"scientific discipline without a large number of thoroughly executed case studies is a discipline without systematic production of exemplars, and a discipline without exemplars is an ineffective one"* (page 219).

3.2 Development of the PC cost model

3.2.1 Defining the cost elements impacted by PC

As discussed in the literature review, there is currently no consensus on the lifecycle impacts of PC and very little empirical evidence provided. Generally researchers have focused their discussions around assembly (Atzeni and Salmi, 2012, Weller et al., 2015, Tuck et al., 2006), supply chain (Oettmeier and Hofmann, 2016, Bianchi and Åhlström, 2014, Aliakbari, 2012), and product quality from tolerance stack-up (Dietrich and Cudney, 2011, Reiher and Koch, 2016).

Current AM cost models also tend to focus on well-structured process-related costs from build preparation to post-processing and do not account for any activities prior to or post manufacturing. Atzeni et al. (2010) and Atzeni and Salmi (2012) are exceptions and include assembly cost based on models looking at relatively simple polymer and metal assemblies. Thomas and Gilbert (2014) and Thomas (2015) identified that many benefits of AM are hidden in ill-structured costs, such as within the supply chain and inventory. Whilst PC might eliminate multiple supply chain components, a better understanding is required based on empirical evidence.

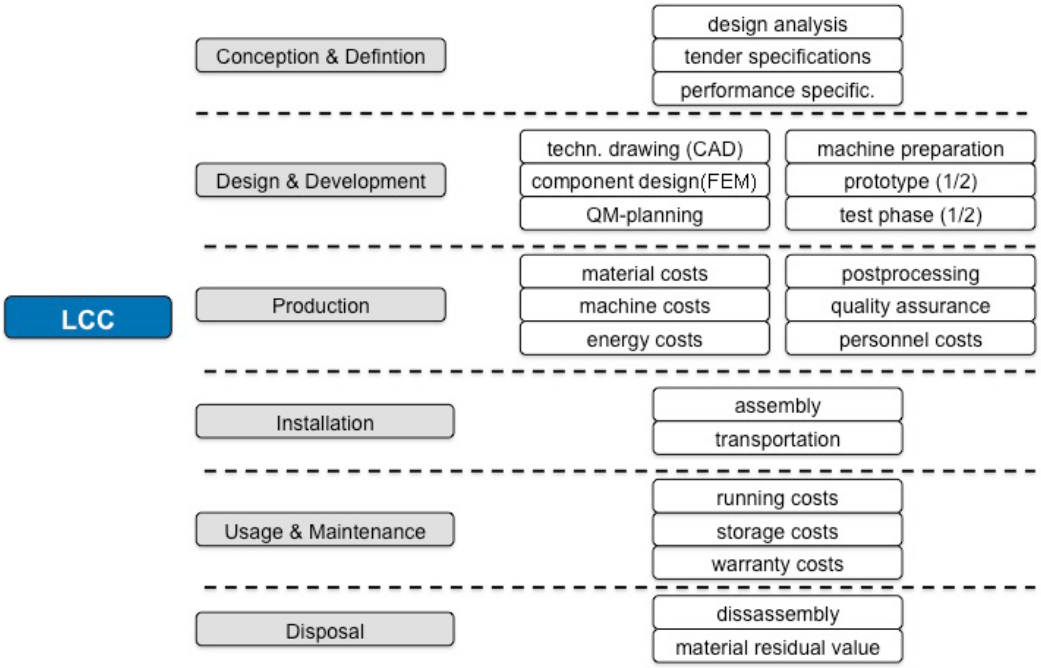


Figure 37: Activity-based cost model based on the intrinsic product lifecycle of aerospace components. Image taken from Lindemann et al. (2013)

The cost elements in this research were adapted from the Lindemann et al. (2013) activity-based costing model based on the intrinsic product lifecycle (Figure 37). To limit the scope of this research, the elements were only defined within the *"Design and Development"* and *"Production"* lifecycle stages. Though research has identified potential benefits from PC within wider lifecycle stages (e.g. reducing maintenance by improving robustness through a reduced tolerance accumulation), there is a considerable lack of robust empirical research. These limits were imposed due to both time and resource constraints.

The cost elements originally defined by Lindemann et al. (2013) within these stages were based on the aerospace industry to compare additively and traditionally manufactured parts. It is a development of previous process cost models to try and account for wider lifecycle impacts, but it does not appropriately reflect the business model or products of the host company. The elements within this research were defined based on activities within *Design & Development* (referred to as *Development*) and *Production* of the host company that might be impacted by the number of parts within an assembly. *Assembly* is defined within Installation by Lindemann et al. (2013), but will be considered within *Production* in this research to better reflect the host company's business model of non-distributed manufacturing. Initially, the activities to define the cost elements were mapped as a simplified consecutive process from component design to quality control prior to delivery, shown in Figure 38.

Process costs – defined by Lindemann et al. (2013)'s model as "*machine preparation, material costs, machine costs, energy costs, and post-processing"* – were not constructed in this research. This decision was made early on as it was clear these costs vary significantly due to machine, material, build time, and post-processing requirements which are ultimately defined by the design of the part. Constructing these would have limited the model to one type of manufacturing process, restricting potential applications. The adopting organisation may also have no knowledge of suitable AM processes prior to completing case studies such as are used within this research.

As discussed in the literature review, a major benefit of AM is that bespoke tooling required for subsequent manufacturing operations (such as moulds for injection moulding and casting) are no longer required. These tools typically require design, analysis, manufacture, and assembly which can incur significant costs. For the host company, investments in tooling is a significant part of their production of components and is supplied by external suppliers. A direct cost for tool related activities is used in this research as it better reflected the business model of the host company.

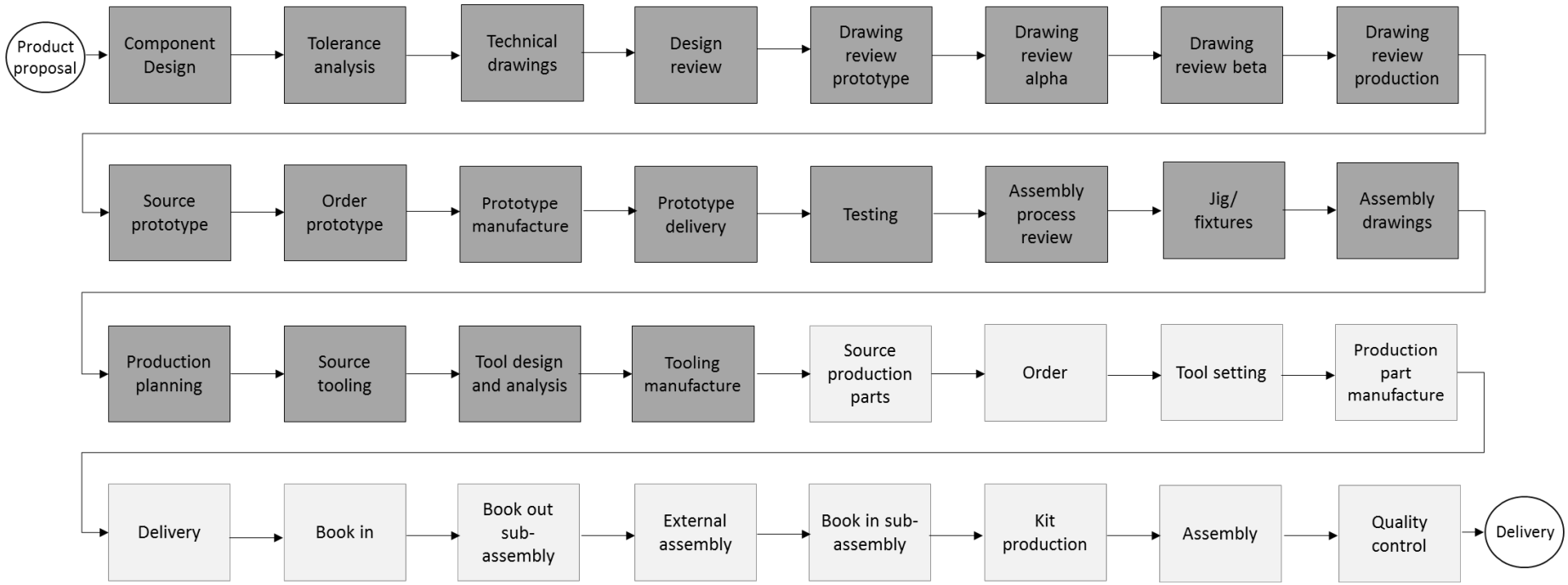


Figure 38: Development (dark grey) and Production (light grey) activities of the host company that might be impacted by the number of parts within an assembly, including ill-structured activities

The cost elements were then grouped into 9 categories shown in Table 4 to help with the development of the model: *Component design, Drawings reviews, Prototyping, Tooling, Supply, Manufacture, Assembly, and Quality control*. Differentiation could then also be made between the up-front one-off costs within *Development*, and yearly recurring costs within *Production* which depend on annual production volumes and number of years the product will be produced. *Tooling manufacture* was considered within *Development* as the low volumes of the host company meant typically retooling was not required unless due to design changes – which were also not considered. These costs could be accounted for within *Tooling manufacture* by future adopting organisations if relevant.

Table 4: Development and Production activities of the host company that might be impacted by PC, grouped into cost categories

Lifecycle stage	Cost category	Cost element
Development (up-front one-off)	Component design	Design
		Tolerance analysis
		Technical drawings
		Design reviews
	Drawing reviews	4-stage gated drawing reviews
	Prototyping	Source prototypes
		Order prototype
		Manufacture prototype
		Deliver prototype
		Test
	Assembly review	Assembly process review
		Jig and fixture design, manufacture, test etc.
		Assembly drawings
		Production planning
	Tooling	Source tooling
		Tool design and analysis
		Tool manufacture
Production (yearly recurring)	Supply	Source production parts
		Order production parts
		Deliver production parts
		Book in to stores
		Book out external sub-assembly
		External sub-assembly
		Book in sub-assembly
	Manufacture	Tool setting
		Mechanical part manufacture
	Assembly	Kit production
		Assemble parts
	Quality control	Align
		Test

3.2.1.1 Refinement of the cost elements

Costs can generally be divided into two categories: well-structured and ill-structured (Thomas and Gilbert, 2014). Whilst well-structured AM costs have typically been associated with labour, material, and machine costs; ill-structured are considered to involve build failure, machine setup, and inventory. Defining the cost model from the perspective of PC meant that some previously ill-structured cost elements could be included in this cost model. Within inventory for example, whilst it might be difficult to calculate exactly how much it costs to manage and store individual parts, this model can still indicate the potential cost difference based on the number of parts in an unconsolidated and consolidated assembly or product.

Several cost elements however remained ill-structured and difficult to quantify in terms of PC: *Design reviews, Testing, Assembly review, Jigs and fixtures, Assembly drawings, Production planning, Sourcing production, External assembly operations,* and *Quality control*. This was due to limited existing research focusing on the lifecycle impacts of PC, that would also not be covered by the sub-assembly level redesign case studies performed in this research.

Whilst reducing part count might indicate fewer design and assembly reviews for example, it is difficult to know how the new design capabilities enabled by AM might impact the time taken to review those designs. Designs may be multi-functional and more complex; but there may also be considerably fewer process limitations to consider. Assembly of sub-assemblies might also still require jigs, but this research only looked at one sub-assembly.

Simplifying assemblies and reducing tolerance accumulation (Dietrich and Cudney, 2011) might increase robustness and indicate reduced quality control procedures, but the build consistency and repeatability of AM processes is discussed as a major limitation to end production applications (Bikas et al., 2015, Salmi et al., 2013, Monzón et al., 2014). These ill-structured elements would require further discussion and research. The manufacturing cost for *Standard parts* also had to be accounted for. The final cost elements defined in this research for quantifying the potential impact of PC on costs are shown in Figure 39.

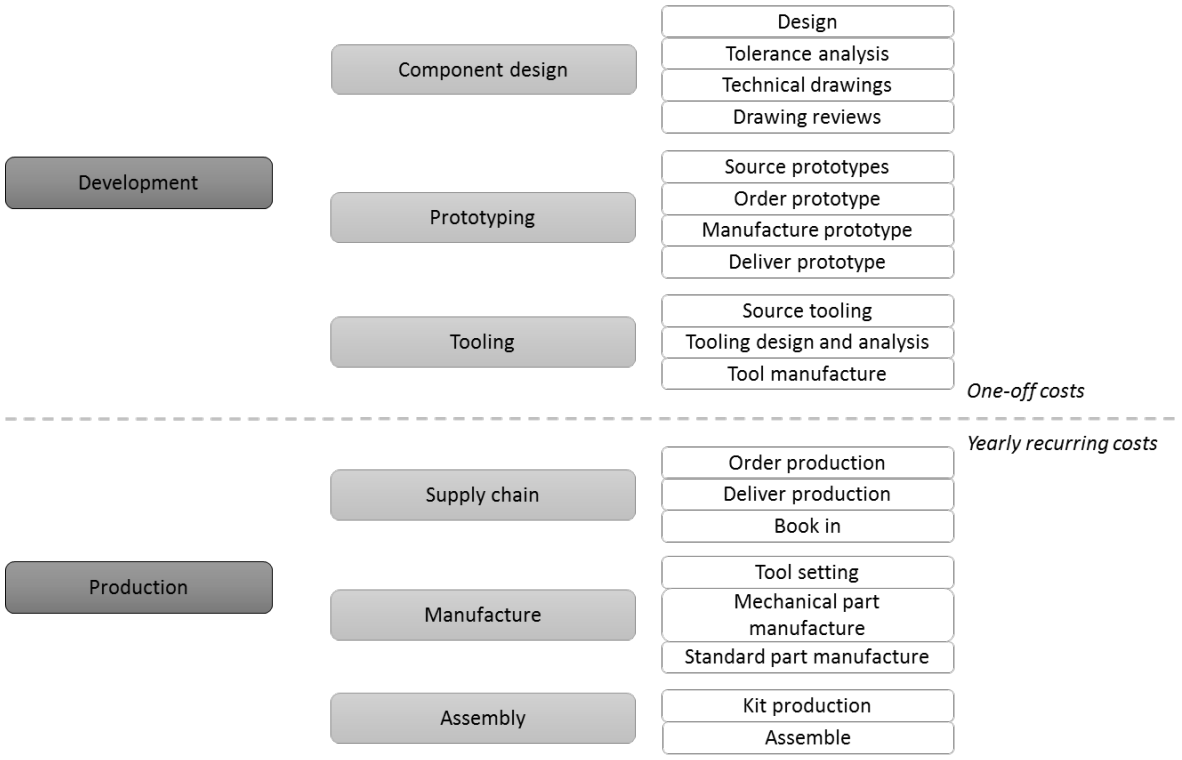


Figure 39: Final cost elements of the PC cost model defined within the Development and Production stages of a product's lifecycle

3.2.2 Definition of terms to appropriately calculate the reduction in part count relevant to the type of activity

To facilitate understanding of the used approach, it is necessary to define several terms in this research. The label "*unit*" is used to quantify the degree of consolidation in terms of a reduction in part count, and is split into *Item* or *Part* depending on whether the cost element is a one-off or recurring activity. Within *Component design* for example, design and technical drawing activities are only performed per individual *Item*, regardless of how many of those are used within the assembly or what the annual production volumes will be. Elements within *Supply chain* however are relevant for each individual *Part* within an assembly and related to production volumes and number of years the product will be produced. Some parts within an assembly may also not require any design but will still require manufacture and assembly. The "reduction in part count" used as the basis to calculate the cost impact of PC is therefore not as simple as just taking the total number of individual "parts" within as assembly.

The descriptor *Mechanical Item* therefore refers to the number of individually designed (bespoke) components contained within the assembly. *Mechanical part* refers to the number of those *Mechanical items* required in the assembly. As discussed, bespoke manufacturing tooling is not required for AM processes. There was therefore a need to differentiate between *Mechanical parts* that were generated via a tooled process (*Tooled mechanical items* and *Tooled mechanical parts*) as these relied on additional activities (and therefore costs) prior to and during production. These parts are counted as a *Mechanical item* or *Mechanical part* for all activities that are not specifically related to tooling, which are *Source tooling, Tooling design and analysis (d&a),* and *Tool manufacture* within the *Tooling* category; and *Tool setting* within *Manufacture*.

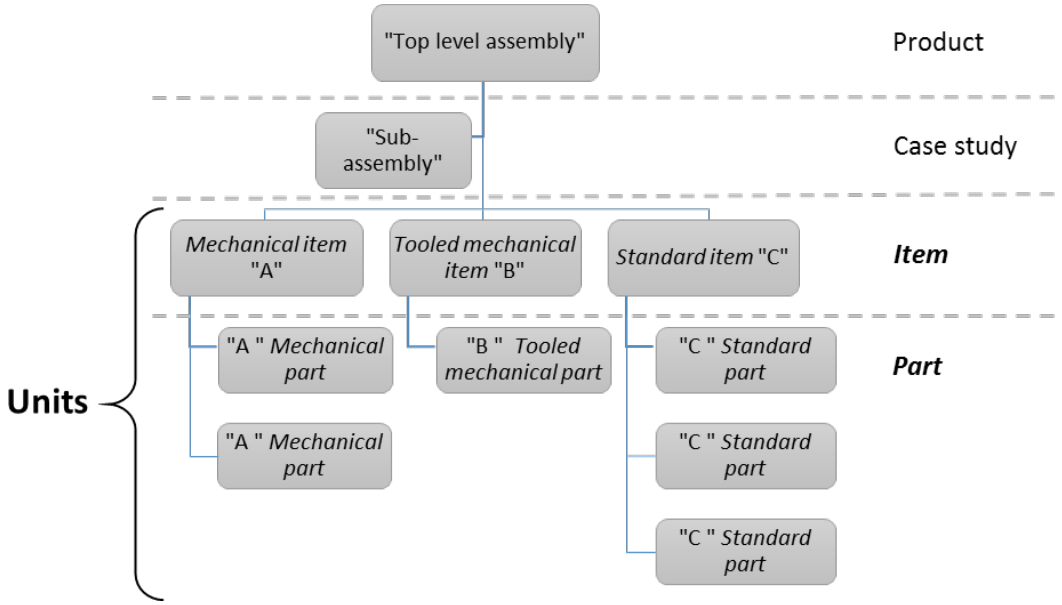


Figure 40: Classification of units to quantify the degree of consolidation in terms of number of parts or units depending on the activity

The term *Standard part* refers to any parts which are not bespoke and are generally bought out (screws, O-rings, nuts etc.). The *Total number of parts* included all *Mechanical parts* and *Standard parts* for calculating assembly costs (equation (1)). Figure 40 illustrates an example breakdown of a sub-assembly per this classification, which has also been used as a graphical tool to show the results of each redesign case study in chapter 4.1.2. This example has a total of 3 *Items* and 6 *Parts*; the total number of *Mechanical items* is 2, and *Mechanical parts* is 3.

$$N_{TOTAL} = N_{MECHPART} + N_{STANDARD} \quad (1)$$

3.2.3 Definition of cost elements as a cost per unit

The final cost elements were expressed in terms of a cost per unit in Table 5. As process costs were out of scope, the model assumed external manufacturing of prototypes, M*echanical parts, Standard parts*, and tooling. These and related activities were therefore expressed as a direct cost whilst the remaining elements were cost rates driven by time and labour cost. Two distinct labour cost rates $\dot{C}_{LABOUR1}$ and $\dot{C}_{LABOUR2}$ were defined by the host company, and all cost elements assume just one person is required for each activity.

It is assumed for *Component design* elements that each *Mechanical item* ($N_{MECHITEM}$) is designed once and can be expressed as a cost rate. The tolerance analysis time however will depend on complexity based on the number of *Mechanical parts* ($N_{MECHPART}$) in the assembly, even if some are identical. This is the only cost element within *Development* which is multiplied by $N_{MECHPART}$.

Sourcing prototypes assumes just one supplier is identified for all the prototypes; whilst *Order*, *Manufacture*, and *Deliver* assume multiple *Prototypes* ($N_{PROTOTYPE}$) are required per $N_{MECHITEM}$. As discussed previously, most tooling costs are expressed as one-off sunk costs per *Tooled mechanical items* ($N_{TOOLITEM}$). The *Production* cost elements needed to reflect annual production volumes, and so were all multiplied by annual production volume (N_{VOLUME}) and number of years the product will be produced (PL).

Table 5: Elements of the constructed cost model

Lifecycle stage	Cost element	Specification	Allocation base (unit)	Symbol
Development - one-off costs independent of production volume	Design	Design time (T_{DES}) multiplied by $\dot{C}_{LABOUR1}$	Number of Mechanical items ($N_{MECHITEM}$)	a
	Tolerance analysis	Tolerance analysis time (T_{TOL}) multiplied by $\dot{C}_{LABOUR1}$	Number of Mechanical parts ($N_{MECHPART}$)	b
	Technical drawings	Technical drawing time (T_{DRAW}) multiplied by $\dot{C}_{LABOUR1}$	$N_{MECHITEM}$	c
	Drawings reviews	Total review time ($T_{REVtotal}$) multiplied by $\dot{C}_{LABOUR1}$		d
	Source prototypes	Prototype source time ($T_{SOURCEprototype}$) multiplied by $\dot{C}_{LABOUR1}$		e
	Order prototype	Prototype order time ($C_{ORDERprototype}$) multiplied by $\dot{C}_{LABOUR1}$	Number of prototypes per Mechanical item ($N_{PROTOTYPE}$)	f
	Manufacture prototype	Prototype cost ($C_{PROTOTYPE}$)		g
	Deliver prototype	Prototype delivery cost ($C_{DELIVERprototype}$)		h
	Tool sourcing discussion	Tool discussion time ($T_{TOOLdiscussion}$) multiplied by $\dot{C}_{LABOUR1}$	Number of Tooled mechanical items ($N_{TOOLITEM}$)	i
	Tooling design and analysis	Tool design and analysis cost ($C_{TOOLINGd\&a}$)		j
	Tooling manufacture	Production tooling manufacture cost ($C_{TOOLING}$)		k
Production - yearly recurring costs dependant on production volume N_{VOLUME} and number of years the product will be produced *PL*	Order production	Production order time ($T_{ORDERproduction}$) multiplied by $\dot{C}_{LABOUR1}$	$N_{MECHPART}$	l
	Deliver production	Production delivery cost ($C_{DELIVERproduction}$)		m
	Book in	Book in time (T_{BOOKin}) multiplied by $\dot{C}_{LABOUR2}$		n
	Tool setting	Tool setting cost ($C_{TOOLsetting}$)	Number of Tooled mechanical parts ($N_{TOOLPART}$)	o
	Mechanical part manufacture	Mechanical part manufacturing cost ($C_{PRODUCTION}$)	$N_{MECHPART}$	p
	Standard part manufacture	Standard part cost ($C_{STANDARD}$)	Number of standard parts ($N_{STANDARD}$)	q
	Kit production	Kit production time(T_{KIT}) multiplied by $\dot{C}_{LABOUR2}$	$N_{MECHPART}$	r
	Assembly	Assembly time ($T_{ASSEMBLY}$) multiplied by $\dot{C}_{LABOUR2}$	Total number of parts (N_{TOTAL})	s

For simplification, the equations specified for each element of the cost model are summarised below in Table 6.

Table 6: Summary of the specifications for each cost element used for the cost model

Symbol	*Specification*
a	T_{DES} x $\dot{C}_{LABOUR1}$
b	T_{TOL} x $\dot{C}_{LABOUR1}$
c	$T_{DRAW\ x}$ $\dot{C}_{LABOUR1}$
d	$T_{REVtotal}$ x $\dot{C}_{LABOUR1}$
e	$T_{SOURCEprototype}$ x $\dot{C}_{LABOUR1}$
f	$C_{ORDERprototype}$ x $\dot{C}_{LABOUR1}$
g	$C_{PROTOTYPE}$
h	$C_{DELIVERprototype}$
i	$T_{TOOLdiscussion}$ x $\dot{C}_{LABOUR1}$
j	$C_{TOOLINGd\&a}$
k	$C_{TOOLING}$
l	$T_{ORDERproduction}$ x $\dot{C}_{LABOUR1}$
m	$C_{DELIVERproduction}$
n	T_{BOOKin} x $\dot{C}_{LABOUR2}$
o	$C_{TOOLsetting}$
p	$C_{PRODUCTION}$
q	$C_{STANDARD}$
r	T_{KIT} x $\dot{C}_{LABOUR2}$
s	$T_{ASSEMBLY}$ x $\dot{C}_{LABOUR2}$

To identify the potential impact of PC on costs it was initially necessary to estimate the total *Development* costs C_{DEV} and the *Production* costs C_{PROD} using the allocation base and equations defined in Table 5 and Table 6:

$$C_{DEV} = (a + c + d + e + \big((f + g + h)N_{PROTOTYPE}\big)N_{MECHITEM} + bN_{MECHPART} + (i + j + k)N_{TOOLITEM} \quad (2)$$

$$C_{PROD} = N_{VOLUME}((l + m + n + p + r)N_{MECHPART})PL + oN_{TOOLPART} + qN_{STANDARD} + sN_{TOTAL} \quad (3)$$

Total cost for the assembly *CA* results from summing up *Development* and *Production* costs:

$$CA = C_{DEV} + C_{PROD} \quad (4)$$

As can be seen from equations (2) and (3), C_{DEV} and C_{PROD} depend on the number of units ($N_{MECHITEM}$, $N_{MECHPART}$, $N_{TOOLITEM}$, $N_{TOOLPART}$, $N_{STANDARD}$, and N_{TOTAL}) in each assembly. This means that the total cost of the assembly under investigation *CA* must be calculated for the current unconsolidated and consolidated assembly. The impact of PC on costs (*IPC)* can then be calculated in terms of a potential cost saving by subtracting the total costs for the consolidated assembly CA_C from the total costs for the unconsolidated assembly CA_{UC}:

$$IPC = CA_{UC} - CA_C \quad (5)$$

3.3 Trialling the model

As discussed, to trial the model it was important that parameters were based on the adopting organisation. PC redesign case studies were therefore performed within the host company to identify a potential reduction in part count using AM, and provide realistic data for the units of an unconsolidated assembly to calculate CA_C. The units for CA_{UC} were based on the number of *Items* and *Parts* in the original unconsolidated assembly of each redesign case study.

The cost and time parameters of the model for the equations of each of the cost elements (T_{DEV}, T_{TOL}, T_{DRAW}, $\dot{C}_{LABOUR1}$, $\dot{C}_{LABOUR2}$ etc.) were defined from data provided by the host company in pound sterling (£) in 2016. As the focus is on PC and there is very limited research to draw on, the same cost and time parameters were initially used for both the consolidated and unconsolidated design, regardless of the manufacturing process. The *Mechanical part manufacture* cost for the consolidated design was then varied to assess what increase in manufacturing costs could be absorbed by other cost savings. The model itself was developed into an Excel-based tool to increase utilisation of the research results in industrial settings.

3.3.1 Identifying the potential reduction in part count using PC redesign case studies

The model in this research depends on comparing the costs for a consolidated assembly to those of an unconsolidated assembly, based on the number of units in each. As this model is proposed for use during the pre-installation phase of AM implementation, the adopting organisation may not have any data with regards to achieving PC and a reduction in part count. It is assumed that without suitable applications, no benefits could be achieved from adopting a new technology. PC redesign case studies were used as an investigative tool to identify the potential for consolidating parts. The units of the consolidated assembly for the cost model analyses can then be based on empirical evidence, ensuring that results are both accurate and relevant.

The case studies were chosen by having a discussion with engineers and personnel from different departments about components and assemblies within current products that are complex, difficult to assembly, have quality control issues, or require a high amount of maintenance and servicing. It was important that no discrimination was made when choosing the case studies based on any initial ideas of what could or could not be consolidated using AM processes. The number of *Items* and *Parts* within their products also varied significantly. The final chosen case studies reflected a representative range of cross-product applications, functionality, and number of unconsolidated parts and items so that results and analyses could be applied across their product range.

Table 7: Summary of redesign case studies chosen for host company with application

Redesign case study	Application	Number of components in unconsolidated assembly
1. Lens and filter mount	Lens, filter, and PCB mount for laser light path	15
2. Double fold optic mount	Optic mount for laser light path	24
3. Feed funnel	Funnel with access lid for feeding dry powder	21
4. Folded air duct	Air duct for dry powder measurements	24
5. Cover door	Instrument cover door for accessing sample holder	9
6. Fibre optic mount	Repositionable fibre optic mount for optic path	19
7. Thermal insulator	Insulate thermal cell from optic bench	4

Components that could not be manufactured using AM processes were out of scope from consolidation: printed circuit boards (PCBs), cables, wires, leads, mirrors, lens', filters, glass, and motors. A case study with a high number of units was considered to have a high consolidation

potential. Table 7 summarises the sub-assemblies that were chosen as redesign case studies for the host company, in terms of the application and total number of components in the unconsolidated design including those which were out of scope from consolidation but would still require assembly.

3.3.1.1 Re-design approach for PC case studies

Though reducing part count has long been a focus of traditional DFMA guidelines, it has been recognised that new methodologies are required to take full advantage of the design freedom of AM processes. The method used for redesigning the case studies is not a focus of this research. However, it is important to discuss some key literature which helped the researcher define a general redesign approach which helped with the consolidation of components resulting in a reduction in part count.

Currently, most PC design methods are for redesigning existing assemblies based on identifying parts suitable for consolidation or elimination, and performing structural and functional optimisation. Rodrigue and Rivette (2010) developed an assembly-level methodology based on identifying candidates for elimination after the concept stage. However, they follow traditional DFMA guidelines that two parts that need to move relative to eachother cannot be consolidated. Yang et al. (2015b) based their consolidation method on integrating functions then performing structure optimisation using finite element analysis to improve performance (Figure 41).

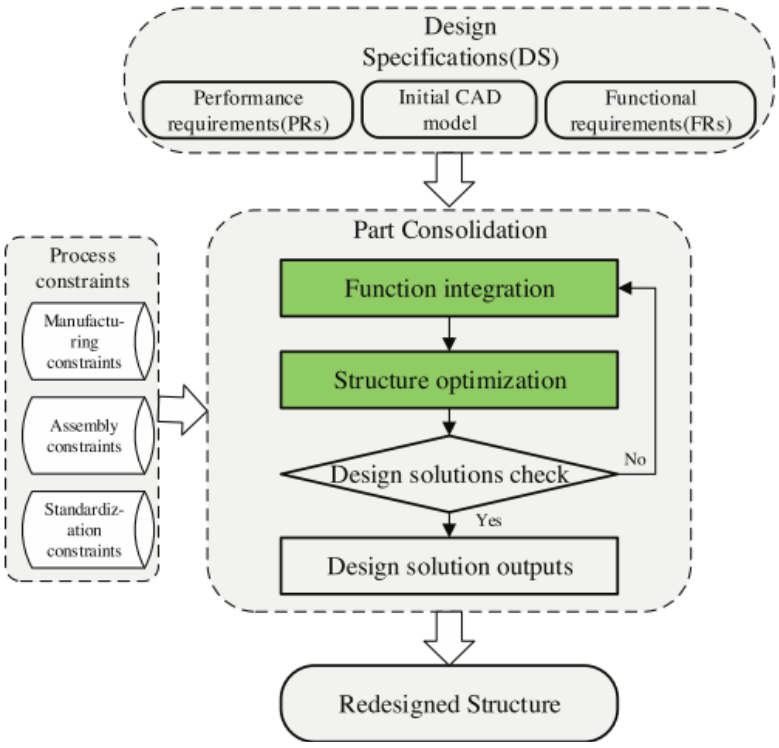
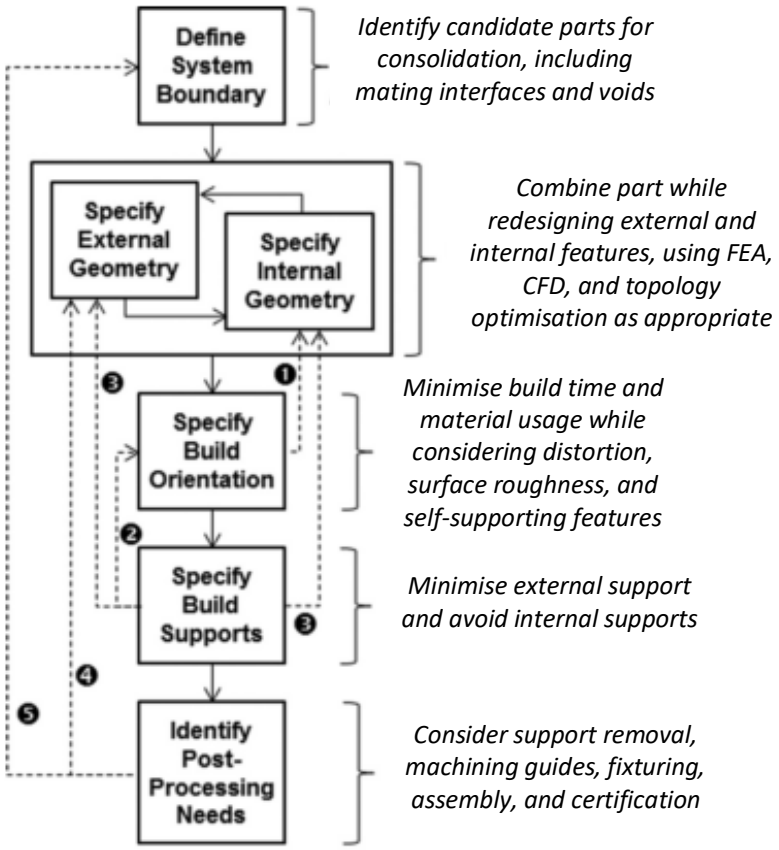


Figure 41: PC design method to embrace the design freedom of AM. Image taken from Yang et al. (2015b)

Schmelzle et al. (2015) developed their methodology based on combining parts and redesigning external and internal features using computational optimisation software, and considering process requirements such as support structures and post-processing (Figure 42). Contrary to Rodrigue and Rivette (2010), they follow the understanding that AM can enable consolidation of parts that need to move relative to eachother, be of different materials, and enable assembly or disassembly of other parts.



Needs for feedback loops

1. Orientation adverse effects internal geometry; redesign
2. Build supports are excessive; modify build orientation
3. Redesign external/internal geometry to reduce build supports
4. Modify external geometry to facilitate post-processing
5. Excessive post-processing, redefine system boundary

Figure 42: (Re)design approach for PC using metal AM. Image taken from Schmelzle et al. (2015)

Tang et al. (2016) method focuses on sustainable design achieved through functionality integration and PC where environmental impact is the focus of the optimisation stage. Liu (2016) define some guidelines for AM-enabled PC based on considerations for structural topology optimisation and build parameters. They conclude that structural topology and build direction should be optimised

concurrently to improve structural performance of consolidated assemblies, which can only be enhanced where material properties are not overly weakened.

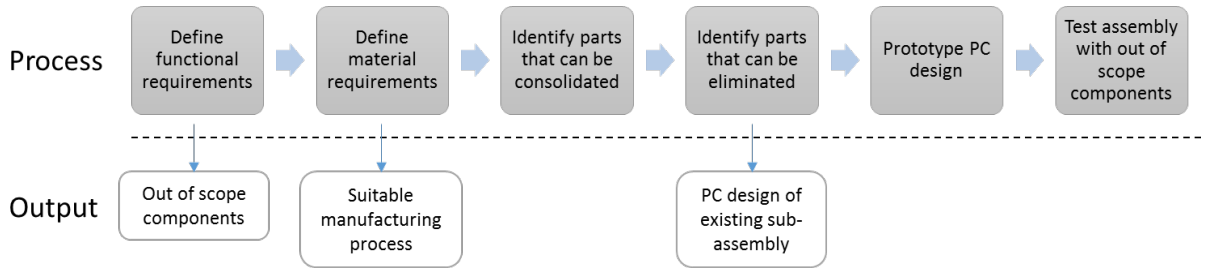


Figure 43: Re-design approach used in this research to consolidate the case study sub-assemblies based on existing literature

The re-design approach used in this research (summarised in Figure 43) was based on a combination of methods outlined above focusing on identifying parts suitable for consolidation. Defining the functional requirements based on the application of the case study helped identify components that were out of scope from consolidation. Fasteners and standard parts such as O-rings and springs were in scope but did not include those required to assemble the case studies to higher level assemblies. A suitable AM process was then chosen based on the material requirements of the application. Choosing the process early on helped to ensure that minimal feature sizes could be manufactured, and process specific requirements such as support structures and powder removal could be considered.

Parts that could be consolidated were then identified, which could reduce or eliminate assembly requirements and other assembly-related parts such as fasteners. Contrary to most DFAM methodologies, the case studies did not undergo any optimisation from a structural, performance, or cost perspective. The focus of this research is on PC and does not construct any process cost models. It therefore would not be able to capture any additional benefits from optimisation such as from weight reduction or reducing build time. The consolidated assemblies were prototyped and tested with the required out of scope components and assembly with higher level assemblies.

3.3.2 Model analyses to be performed for assessing the impact of PC on costs

The cost and time parameters summarised in Table 5 and Table 6 were defined by using existing figures provided by the host company, or by calculating the mean cost or time across a range of products. These calculations were performed with close supervision and input from representatives

from the host company, but details cannot be disclosed for confidentiality reasons. Defining these parameters should be the responsibility of the adopting organisation, and would depend greatly on their own business model. A framework for enabling future adopting organisations to adopt the model and perform their own calculations during their pre-installation phase is presented in section 5.4.

Once the cost and time parameters have been defined by the host company, the model could be used to calculate the potential cost saving from PC. The results of the model were expressed in terms of a percentage cost saving, based on each individual case study and as the average saving across all the case studies. The percentage contribution of each cost element to *Development*, *Production*, and *Total* costs was calculated to compare the results to existing literature in terms of most significant lifecycle stages and activities.

To determine which part-type the host company should focus on consolidating to achieve the biggest cost savings, a simplified linear regression was calculated for percentage production cost saving against percentage consolidation. This could then be used to predict potential cost saving based on a reduction in part count. The co-efficient of determination (R-squared) value for each part type was also calculated to assess how closely the model represents the data gathered, and therefore which linear regression can be used with the most confidence (see section 4.2.3).

3.3.2.1 Varying Mechanical part manufacturing costs

Originally, the same costs and times were used within the model for both the unconsolidated and consolidated design. However, current research on the cost effectiveness of AM processes versus traditional processes often finds AM "too expensive", particularly for medium to high production volumes (Khajavi et al., 2014). AM process costs vary significantly between and within different process categories such as material deposition versus powder bed fusion due to variations in machine, material, and labour costs (Leary et al., 2014, Munguía et al., 2008). The design of a part will also significantly impact the build time and material usage and therefore manufacturing cost, which resulted in the definition of optimisation stages within nearly all AM design methodologies. AM costs should therefore be calculated on a case by case basis, after designs have been optimised to improve functional performance and reduce build time and material usage.

The model was developed to enable different *Mechanical part manufacture* cost (cost element *p*) for the unconsolidated and consolidated design to understand the impact of manufacturing costs on potential cost savings. To simplify the analysis and due to a lack of empirical data or evidence, it was

assumed that prototype manufacturing costs and number of prototypes required would be the same for both designs. This meant that C_{DEV} (Equation (2)) was not adapted and the *Development* cost elements remained the same for both designs. Cost element *p* within C_{PROD} (Equation (3)) had to be differentiated between for each design (unconsolidated and consolidated) to become p_{UC} or p_C. C_{PROD_UC} and C_{PROD_C} could therefore be calculated as shown in equations (6) and (7):

$$C_{PROD_UC} = N_{VOLUME}((l + m + n + p_{UC} + r)N_{MECHPART})PL + oN_{TOOLPART} + qN_{STANDARD} + sN_{TOTAL} \quad (6)$$

$$C_{PROD_C} = N_{VOLUME}((l + m + n + p_C + r)N_{MECHPART})PL + oN_{TOOLPART} + qN_{STANDARD} + sN_{TOTAL} \quad (7)$$

The total cost for each assembly with varying *Mechanical part manufacture* cost *CA',* therefore results from summing up *Development* and *Production* costs for each design:

$$CA'_{UC} = C_{DEV} + C_{PROD_UC} \quad (8)$$

$$CA'_{C} = C_{DEV} + C_{PROD_C} \quad (9)$$

The impact of PC on costs with different *Mechanical Part Manufacture* costs *(IPC')* can be calculated in terms of a potential cost saving by subtracting the total costs for the consolidated assembly CA'_C from the total costs for the unconsolidated assembly CA'_{UC}:

$$IPC' = CA'_{UC} - CA'_{C} \quad (10)$$

By varying the *Mechanical part manufacturing* cost (cost element *p*) for the consolidated design, the company could better understand what increase in manufacturing cost for the consolidated design could be absorbed by cost savings in other elements. Calculations could also be performed to understand different scenarios and the impact of future developments in AM processes. The case studies in this research did not undergo any optimisation, meaning they would not reflect realistic AM manufacturing costs. As originally the same costs for the consolidated and unconsolidated design were used for the cost model, cost element p_c could be varied as a percentage of p_{UC}. The potential cost saving from PC was therefore also calculated with p_c costs as 50%, 100%, 200@, 300%, and 400% percent of the unconsolidated *Mechanical part manufacture* cost (p_{UC}).

The percentages chosen for these subsequent calculation were based on a combination of existing research into current and future AM costs, the experience of the researcher, and the production volumes of the host company. AM is typically most cost effective for low production volumes. The host company would be considered low volume at under 2000 per year, and therefore could assume smaller increases and savings in manufacturing costs when using AM compared with traditional processes. Research also predicts significant development of AM processes, helping to increase efficiency and productivity and reduce overall costs. A manufacturing cost smaller than that of the unconsolidated design (50%) was therefore included along with more significant increases in cost (up to 400%) to cover a broad spectrum of current and future possibilities.

3.3.3 Improving utilisation of the cost model

"Knowledge utilisation" is described by Landry et al. (2001) as *"a field of research concerned with factors explaining the utilisation of scientific and technical knowledge by decision makers and those in professional practices"* (page 396), focusing on increasing the utilisation of research results. In the context of this research, whilst the model developed as an equation in chapter 3.2.3 will provide results in terms of a potential cost saving, it is not realistic to use it in this form in an industrial setting when multiple complex calculations and analyses may be needed in a time-pressure environment.

The implementation process following Voss (1988) 3-phases is complex and requires it to be robust to ensure success. The multiple benefits and complex interactions of AM with an organisation's business model could further increase the complexity of decisions to be made throughout the implementation process. This implies the need for a tool which can be adapted easily by organisations, performing calculations quickly and enabling the results to be presented graphically in forms that can be easily understood by decision-makers.

Excel was the chosen platform for the PC cost model presented in this research due to its capabilities to manage a large amount of data and complex calculations which can be adapted easily and displayed graphically, enabling different analyses to be performed. As well as the cost elements, which are based on the host company in this research, the parameters of the model (*Units*, times and costs) which would need to be adapted to the adopting organisation are summarised in Table 8.

Table 8: Parameters of the model which need to be defined prior to using the PC cost impact tool

Unit	**Time**	**Costs**
Mechanical items per assembly	Design per mech item	Prototype manufacture per prototype per mech item
Mechanical parts per assembly	Drawing per mech item	Prototype delivery per prototype per mech item
Prototypes per mechanical item per assembly	Tolerance analysis per mech part	Tooling design and analysis per tooled mech item
Tooled mechanical items per assembly	Drawings reviews per mech item	Tooling Manufacture per tooled mech item
Tooled mechanical parts per assembly	Prototype source per mech item	Tool setting per tooled mech part
Yearly production volumes	Prototype order per prototype per mech item	Deliver production per mech parts
Standard parts per assembly	Tooling discussion per tooled mech item	Mechanical part manufacture per mech part
Total number of parts per assembly	Order production per mech part	Standard part manufacture per standard part
	Book in per mech part	Labour cost rate 1
	Kit production per mech part	Labour cost rate 2
	Assembly time per part	

4 Results

The cost model used in this research to calculate the potential impact of PC on costs was developed in section 3.2 of the methodology, based on the host company treated as a single case study. This chapter outlines the research results in three main sections, related to objectives B, C, and D. Section 4.1 will be the results of the PC redesign case studies used to identify the potential for PC for the host company. A robust pre-installation phase relies on using data from the adopting organisation, and should include evidence of what degree of consolidation could be achieved using the technology being investigated for implementation. The consolidated design of each sub-assembly will be presented, followed by the results of the consolidation in terms of the number of *Items* and *Parts* in each design. The Terminology used to quantify the degree of consolidation related to different types of cost element is described in section 3.2.2.

Section 4.2 will present the results of the PC cost model trial, in terms of the potential cost savings from PC for the host company. A breakdown of calculations based on the degree of consolidation achieved by each redesign case study is presented in section 4.2.1, followed by the percentage contribution of each cost element in section 4.2.2 to identify the most significant lifecycle stages and compare to results from current research. The correlation analysis to identify which part type has the most significant impact on potential cost savings through consolidation is shown in section 4.2.3. The impact of varying the *Mechanical part manufacture* cost (described in section 3.3.2.1 of the methodology) is covered in section 4.2.4. The Excel-based PC cost model utilisation tool developed to increase utilisation by other adopting organisations is shown in section 4.3. It is important to note that no real cost figures are shown in this thesis due to the confidential nature of this research.

4.1 The potential for part consolidation identified using redesign case studies

4.1.1 Background to the redesign case studies chosen for host company

As per the design approach defined in section 3.3.1.1, the seven redesign case studies chosen for the host company are summarised in Table 9 in terms of the functional requirements, out of scope components, material requirements, and suitable AM processes. Three of the assemblies had to position various components critical for material characterisation and measurements. Whilst one of these also had to be repositionable (case study 6), the other two were static (case studies 1 and 2). Two case studies (3 and 4) were required for feeding and directing the material that will be characterised. Case study 5 is a cover door which is relevant for all products regardless of function and application. Case study 7 is required for insulation for high temperature functionality.

Only two case studies (4 and 5) required no assembly of out of scope components to the consolidated design. Case study 7 had to route and secure a cable from another assembly, which was therefore not counted as an out of scope component for this case study but was an important consideration for the consolidated design. Case study 1 had to be conductive, and case study 6 stable in high temperatures making metal PBF using Aluminium suitable for their production.

Case studies 2, 3, 4, and 5 were all suitable for polymer PBF using a PA12. Case studies 3 and 5 were also customer facing imposing aesthetic requirements, and so could be dyed black (or other colours) to fit in with brand language. Case study 7 required a V-0 flame retardant (FR) certification with a low thermal coefficient for efficient insulating properties, limiting material and process option to PBF using a PA12 FR V-0 material.

Table 9: Summary of functional requirements, out of scope components, material requirements, and suitable AM processes for each redesign case study

Case study	Functional requirements	Out of scope components	Material requirements	AM process/es
1. Lens and filter mount	Hold filter, lens, & PCB in position, ground PCB	Filter, lens, PCB (x3)	Conductive	PBF Aluminium
2. Double fold optic mount	Hold optics in position	Mirror, lens x2, dust window (x4)	Dimensionally stable over time	PBF PA12
3. Feed funnel	Feed dry sample in to instrument, window for visual	Transparent window (x1)	Aesthetic/customer interaction	PBF PA12 + dyed black
4. Folded air duct	Direct air flow	None (x0)	Dimensionally stable over time	PBF PA12
5. Cover door	Front cover door for instrument	None (x0)	Aesthetic/customer interaction	PBF PA12 + dyed black
6. Fibre optic mount	Hold and position fibre optic cable in place	Fine pitch adjustment screws x2, fibre optic cable (x3)	Dimensionally stable over time and temperature variations (-40°C to +50°C)	PBF Aluminium
7. Thermal insulator	Insulation	None (x0)	Flame retardant V-0 with low thermal coefficient	PBF PA12-FR

4.1.2 The consolidated designs

4.1.2.1 Redesign case study 1 – lens and filter mount

The function of case study 1 was to hold a lens, blue obscuration filter, and PCB in alignment for an optical path to measure particle size. The original unconsolidated design was made of two injection moulded components that were assembled around the filter and lens and glued together. The PCB was then assembled using screws, along with a metal bracket for grounding the PCB through other parts within the assembly. Figure 44 shows the exploded assembly for the unconsolidated design and breakdown of units into *Mechanical, Tooled mechanical,* and *Standard items* and *parts* as described in section 3.2.2, excluding any out of scope components.

Utilising the design freedom of AM processes for undercuts and complex re-entrant shapes meant that the two injection moulded components could be consolidated, and the lens and filter assembled using slots. The four screws for assembling the PCB were maintained to ensure contact with the conductive mount (see chapter 5.1.2). Prototypes were manufactured using material extrusion in ABS and PBF in PA12, to verify assembly. The final design was manufactured using powder bed fusion in Aluminium. Figure 45 shows a photo of the consolidated design and the breakdown of units.

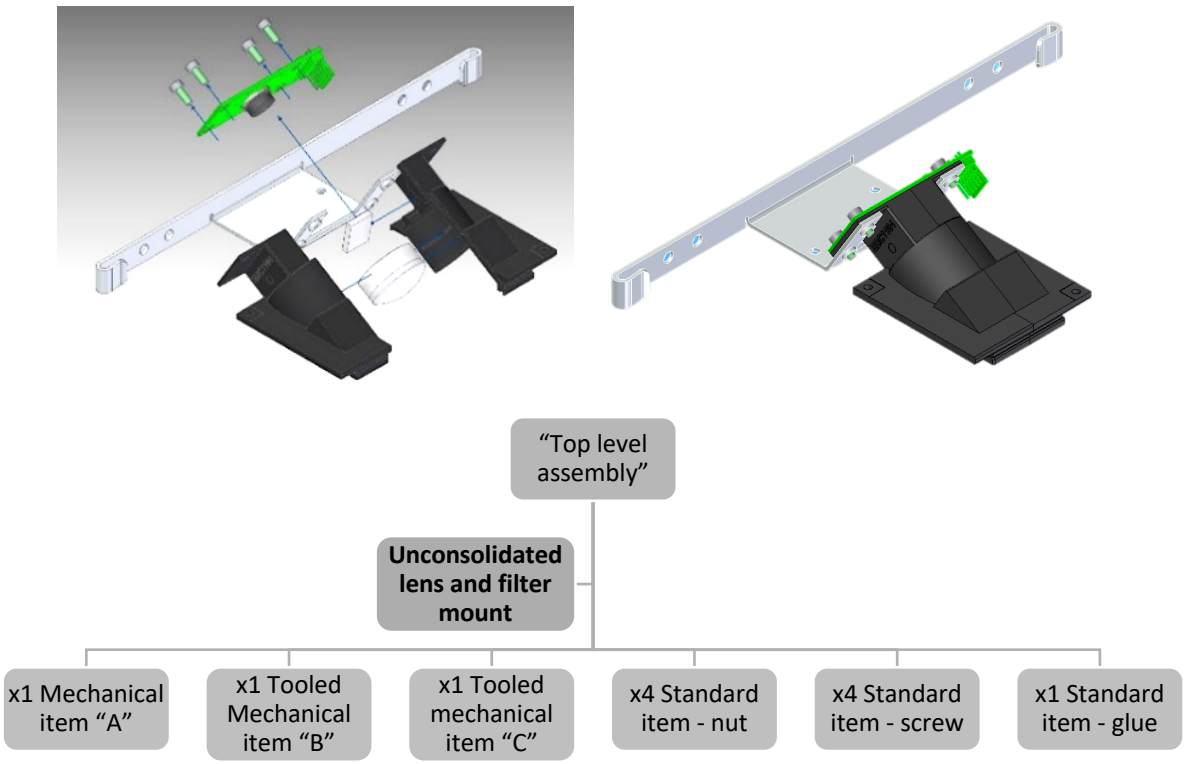


Figure 44: Redesign case study 1 – Lens and filter mount: unconsolidated design and breakdown of units

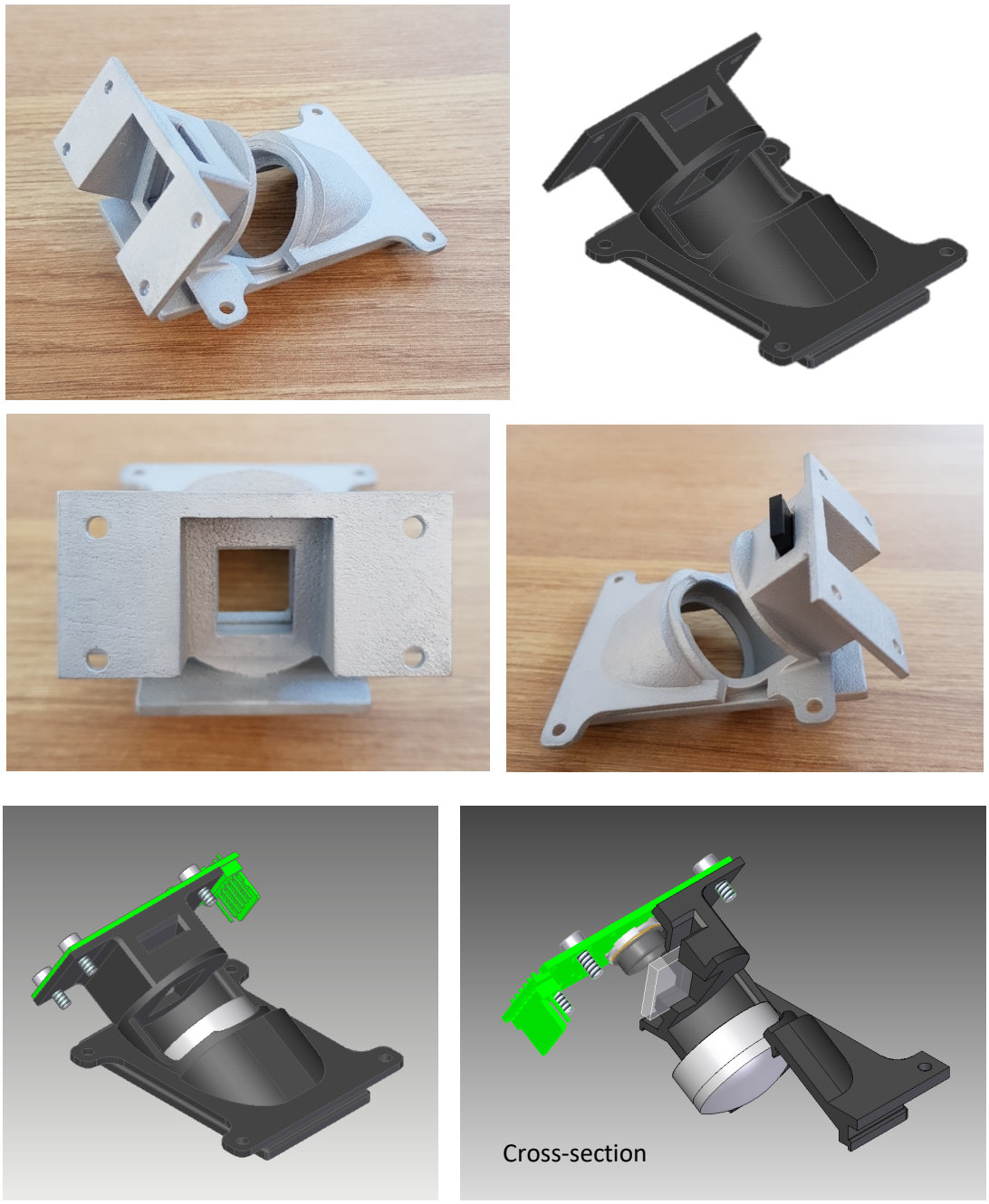


Figure 45: Redesign case study 1 – Lens and filter mount: consolidated design and breakdown of units

4.1.2.2 Redesign case study 2 – double fold optic mount

Case study 2 was an assembly to hold four optics in a double fold alignment on an optical path for particle sizing. The original unconsolidated assembly used separate machined components with screws and O-rings to assemble the optics and secure them in place, with a complex internal channel for enclosing the light path around two 90° bends. Figure 46 shows the exploded assembly of the unconsolidated design along with the breakdown of units.

Using PBF with PA12 meant that the flexibility of the material and capability of the process for undercuts enabled elastic force connections to be designed to assemble the optics. The optics were held securely in place, with a slot in the bottom of the design to enable disassembly for service, repair, or end of life purposes (see chapter 5.1.2). Figure 47 shows the consolidated design along with the breakdown of units.

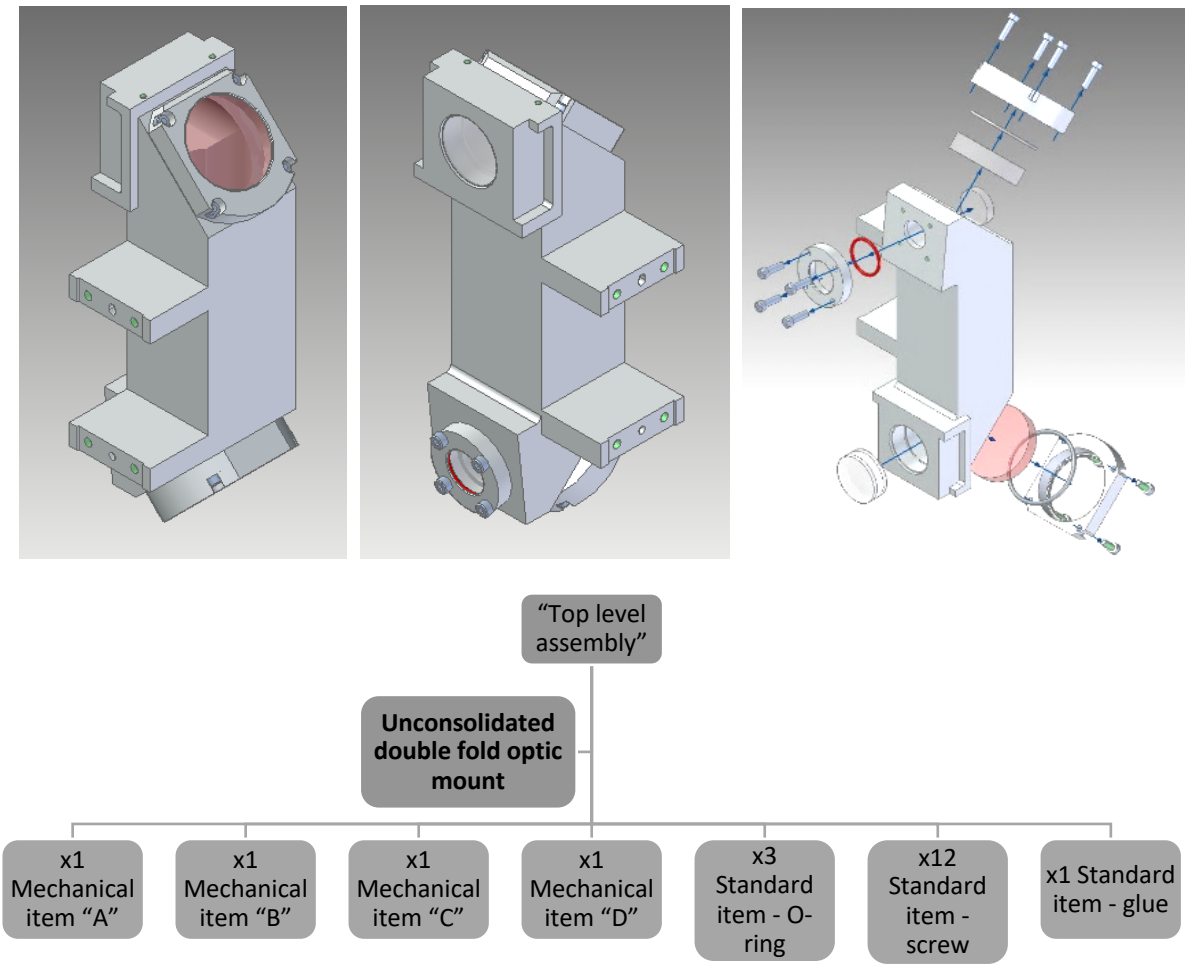


Figure 46: Redesign case study 2 – double fold optic mount: unconsolidated design and breakdown of units

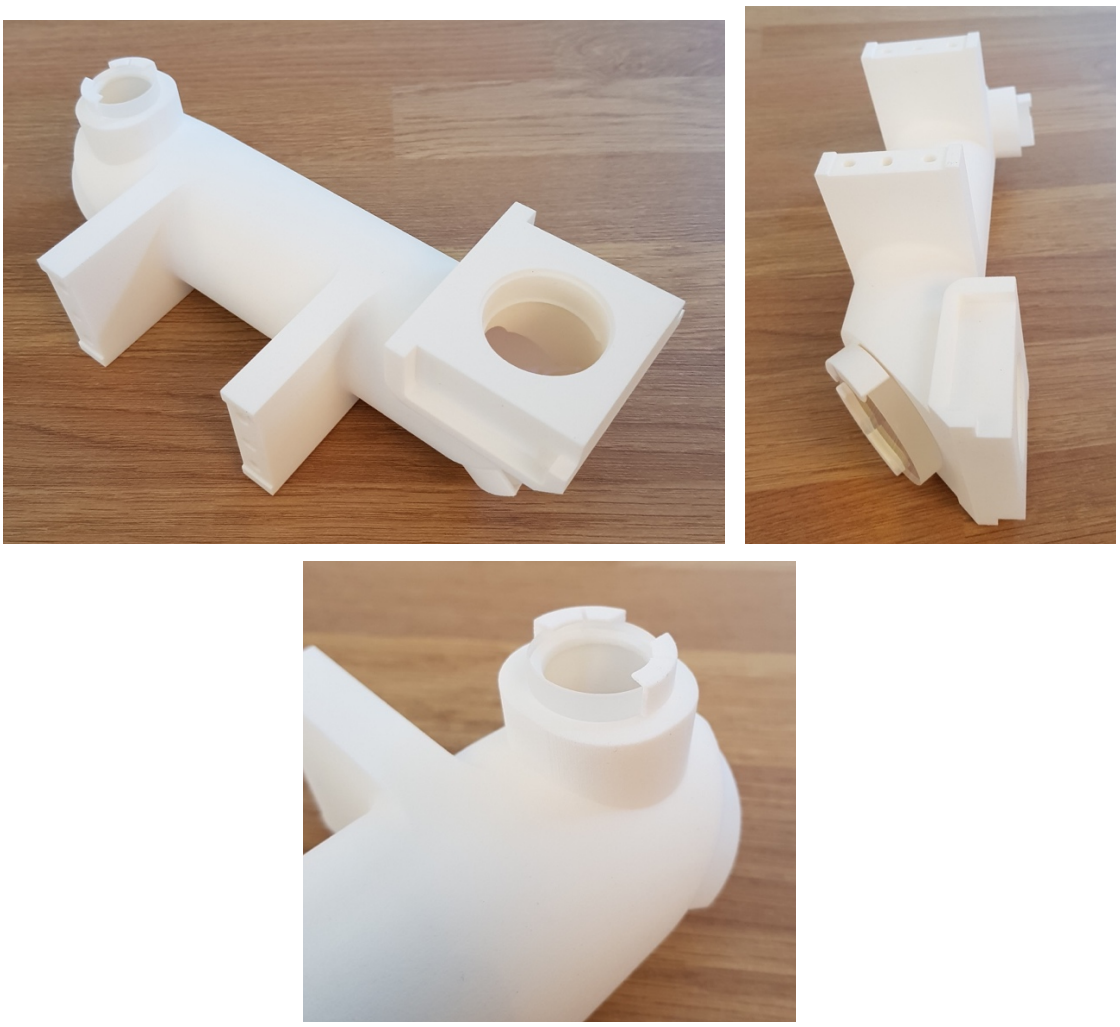


Figure 47: Redesign case study 2 – double fold optic mount: consolidated design and breakdown of units

4.1.2.3 Redesign case study 3 – feed funnel

Case study 3 was a funnel used for feeding dry particle samples for measurement. It consisted of a machined funnel with a hinged lid, which also had a window for viewing the sample attached to the lid using screws. The lid was then secured when closed using magnets in both halves of the funnel. Figure 48 shows the exploded assembly of the unconsolidated design and breakdown of units.

The consolidated redesign took advantage of the ability to integrate hinges using PBF, and snap-fits for assembling the window and securing the closed lid in place (see chapter 5.1.2). It was then dyed black for aesthetic purposes. Figure 49 shows the consolidated design and breakdown of units.



Figure 48: Redesign case study 3 – feed funnel: unconsolidated design and breakdown of units



Figure 49: Redesign case study 3 – feed funnel: consolidated design and breakdown of units

4.1.2.4 Redesign case study 4 – folded air duct

Case study 4 was a folded air duct for directing airflow for dry particle measurements, and consisted of multiple injection moulded components assembled with two fins to reduce air flow turbulence. Screws, glue, tree clips, O-rings and silicone sealant were used to ensure it was airtight. Figure 50 shows the exploded assembly of the unconsolidated design and breakdown of units.

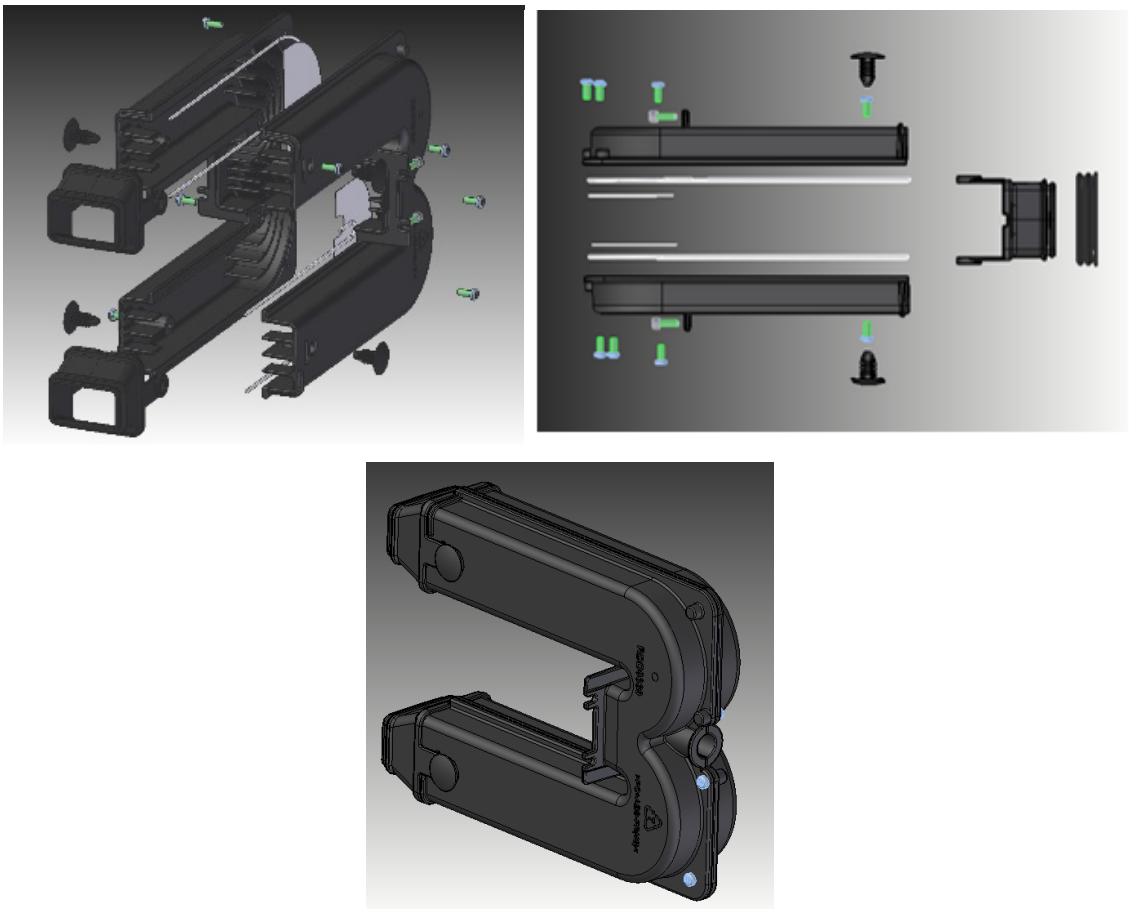


Figure 50: Redesign case study 4 – folded air duct: unconsolidated design and breakdown of units

The consolidated redesign utilised the design freedom of PBF fusion to consolidate the injection moulded components into one part. A benefit of using this process for such a complex internal geometry was that the support material was unsintered build powder making it easier to remove post-process than other processes. The components previously required to make the assembly airtight were no longer needed, and there no assembly of any other out of scope components. Figure 51 shows the consolidated design and breakdown of units.

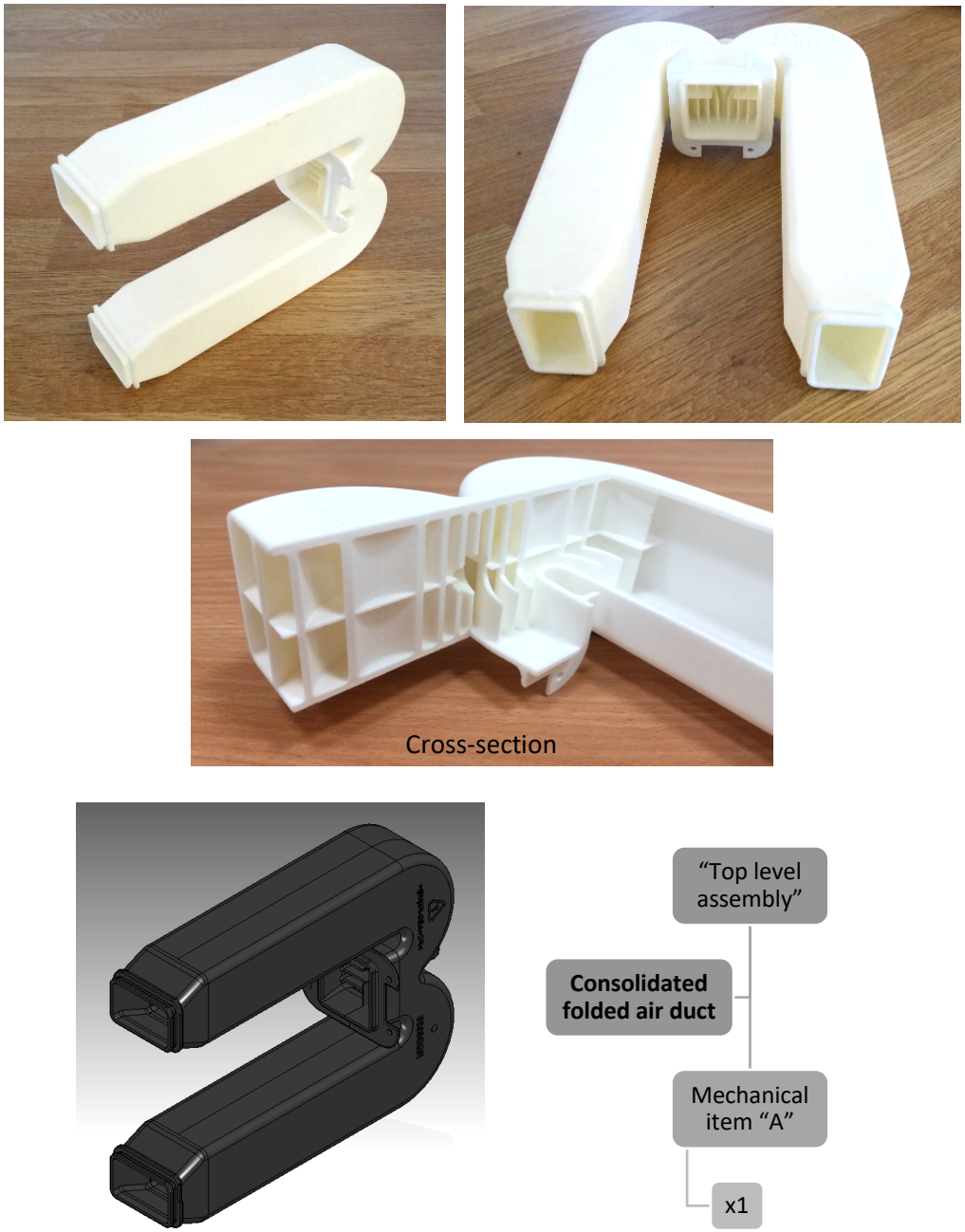


Figure 51: Redesign case study 4 – folded air duct: consolidated design and breakdown of units

4.1.2.5 Redesign case study 5 – cover door

Case study 5 consisted of multiple machined and sheet metal parts which were welded together or assembled using screws for an instrument cover door. Two bearings were assembled by pushing into the axle and held in place by friction. The door enables customer access to internal functions of the instrument. Figure 52 shows the exploded assembly of the unconsolidated design and breakdown of units.

These parts were consolidated using the design freedom of AM, helping eliminate both welding and other assembly activities. The handle and bearings could also be consolidated to the main door components eliminating the screws needed to hold the handle in place. The final design was manufactured using PBF, and dyed black for aesthetic purposes. Figure 53 shows the consolidated design and breakdown of units. This design required no assembly of out of scope components.



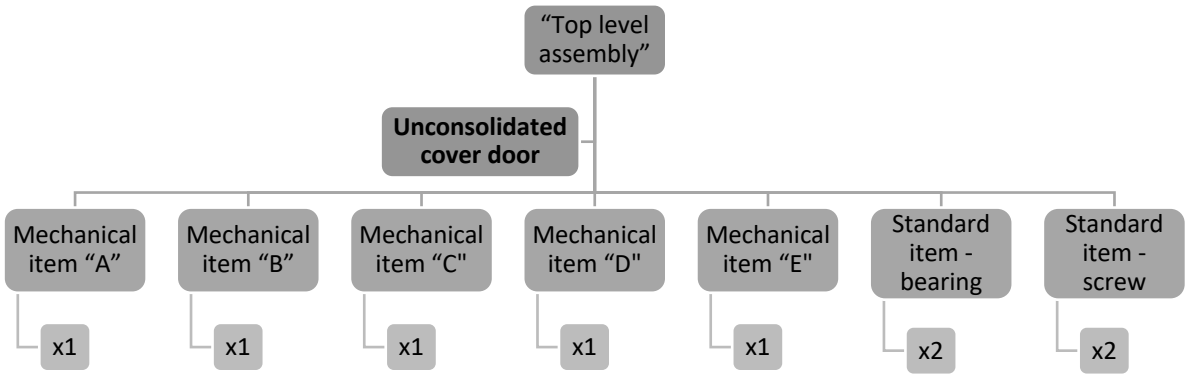


Figure 52: Redesign case study 5 – cover door: unconsolidated design and breakdown of units



Figure 53: Redesign case study 5 – cover door: consolidated design and breakdown of units

4.1.2.6 Redesign case study 6 – fibre optic mount

Case study 6 consisted of two machined parts requiring assembly with multiple screws, pins, springs, and washers to enable adjustable alignment of a fibre optic cable in an optic path. The adjustment was enabled using fine pitch screws which were out of scope from consolidation due to both resolution and accuracy limitations of AM processes. Figure 54 shows the exploded assembly of the unconsolidated design and breakdown of units.

The consolidated design utilised design complexity and varying wall thickness to consolidate the parts and enable pitch and yaw adjustability using flexure hinges, but still required a screw to secure the fibre optic cable (see chapter 5.1.2). Two (out of scope) fine pitch screws were required to adjust the position of the fibre optic cable. The final design was manufactured using PBF in Aluminium for its strength and high thermal co-efficient. Figure 55 shows the consolidated design and breakdown of units.

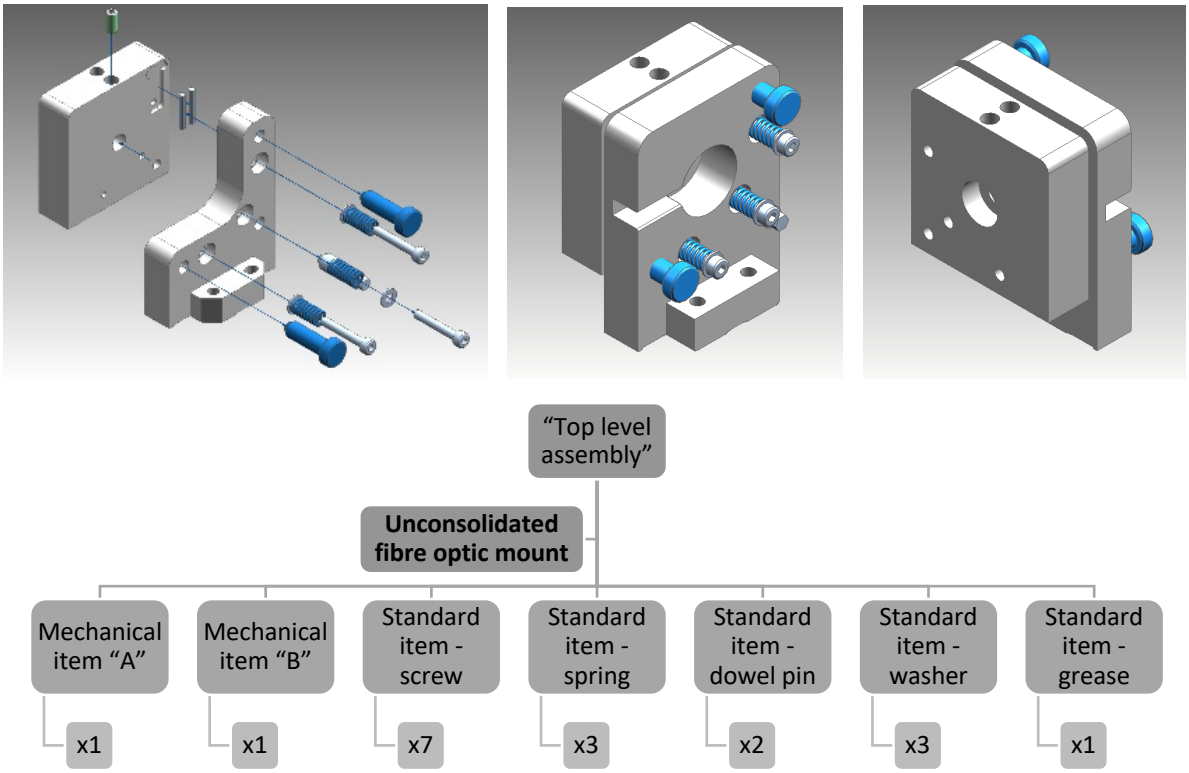


Figure 54: Redesign case study 6 – fibre optic mount: unconsolidated design and breakdown of units

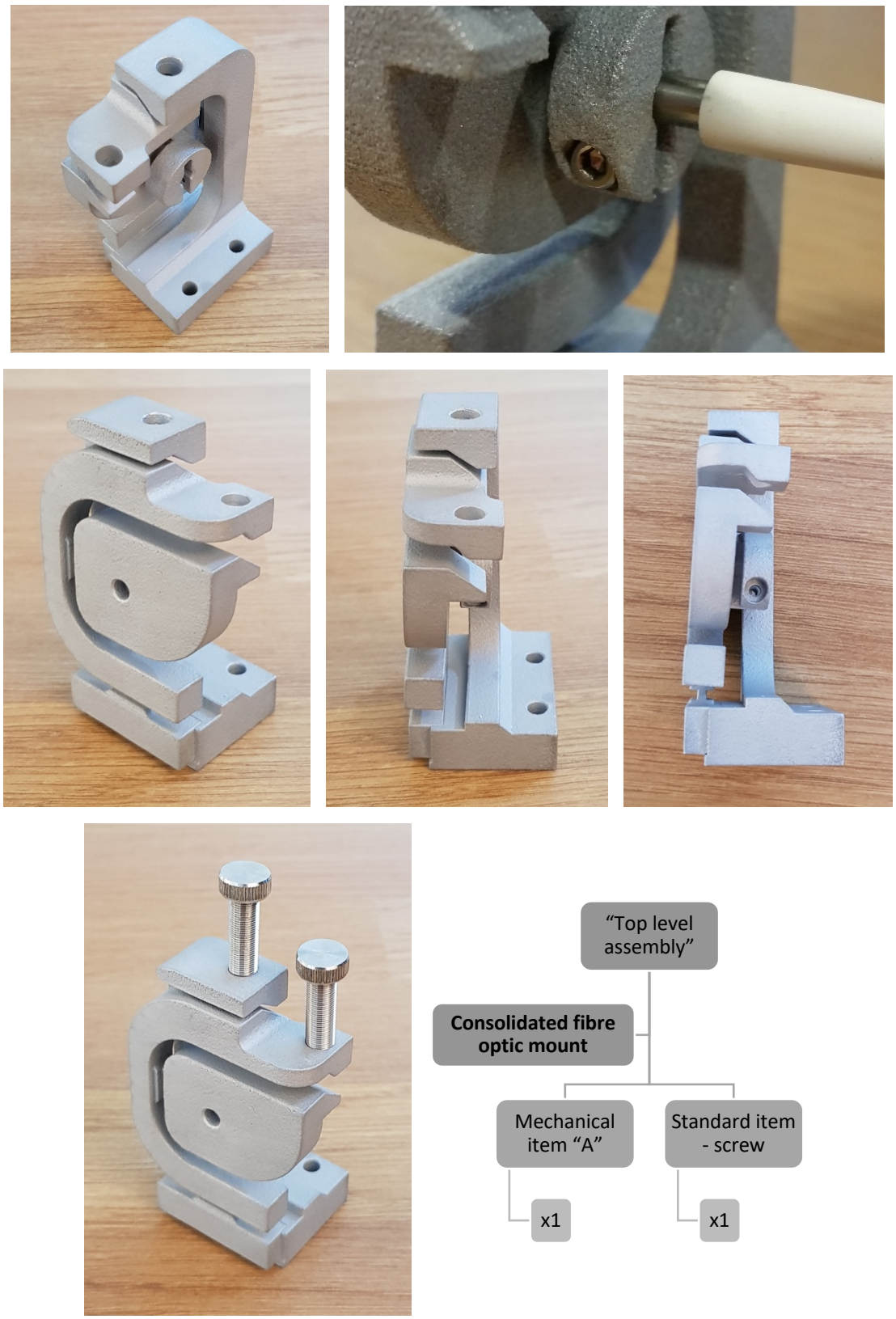


Figure 55: Redesign case study 6 – fibre optic mount: consolidated design and breakdown of units

4.1.2.7 Redesign case study 7 – thermal insulator

Case study 7 was an injection moulded thermal insulator for protecting an optical bench from high temperatures required for particle characterisation. It also served as a fixture point for a cable clip to a cable from another assembly. Figure 56 shows the exploded design for the unconsolidated assembly and breakdown of units, and was the simplest assembly in terms of the original number of items and parts.

The consolidated design took advantage of the design freedom enabled by PBF using a flame retardant PA12, to consolidate the cable clip without requiring a separate screw (see chapter 5.1.2). Figure 57 shows the consolidated design and breakdown of units.

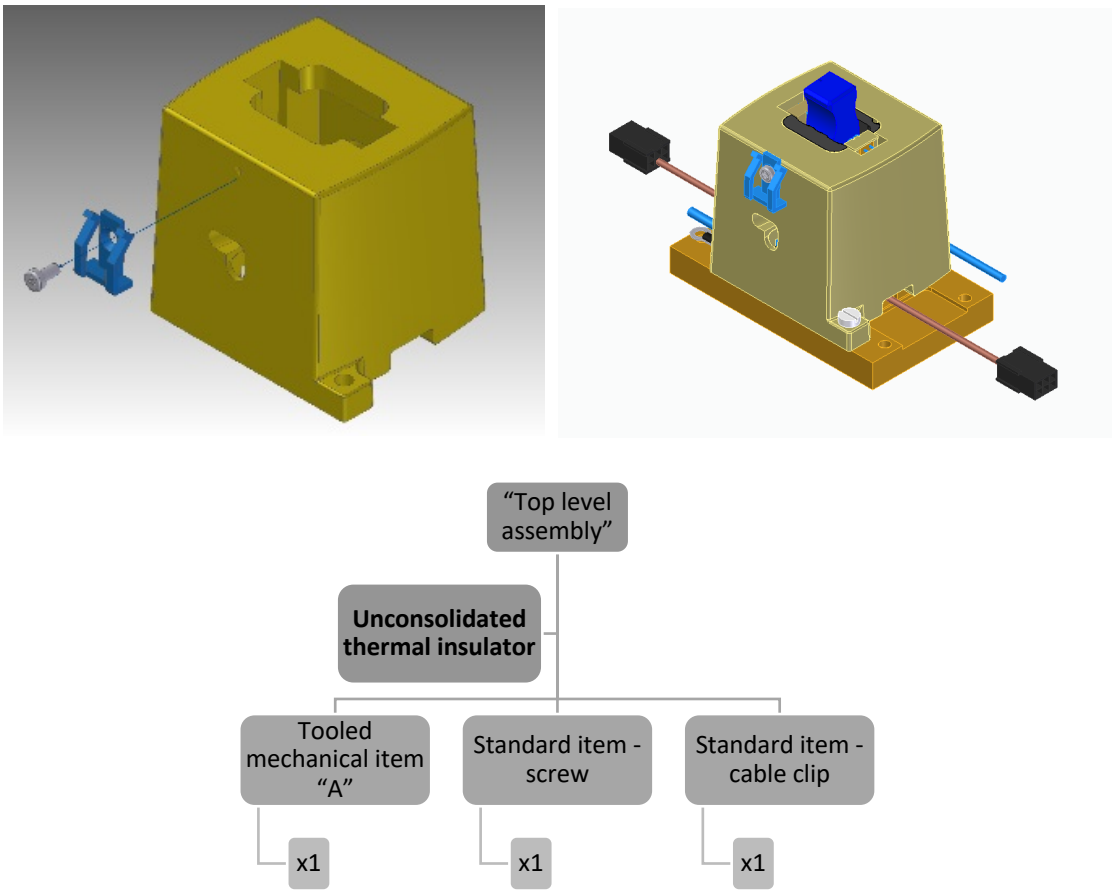


Figure 56: Redesign case study 7 – thermal insulator: unconsolidated design and breakdown of units

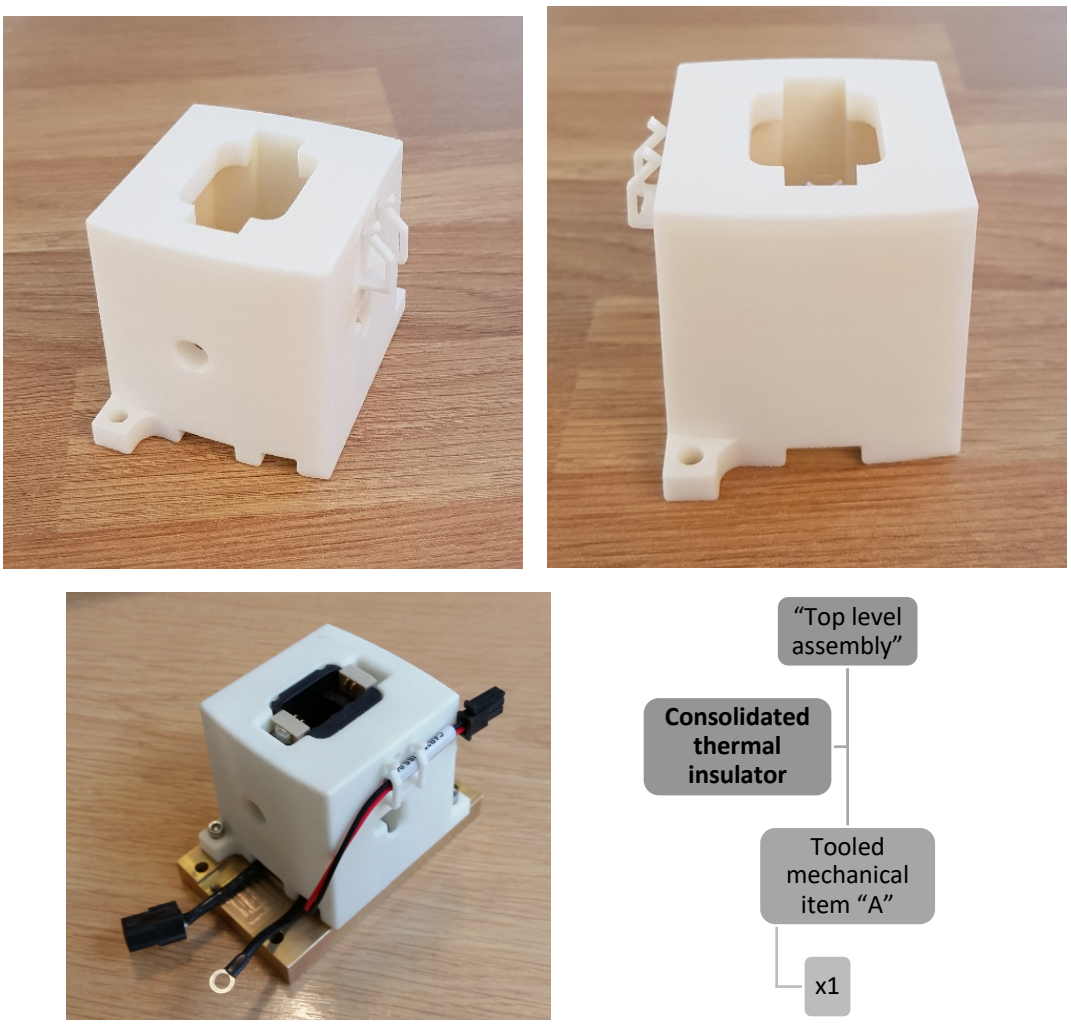


Figure 57: Redesign case study 7 – thermal insulator: consolidated design and breakdown of units

4.1.3 Number of Items and Parts in the unconsolidated and consolidated assemblies

Table 10 presents the case studies in terms of the number units for the unconsolidated and consolidated design, and the percentage reduction achieved by each of the redesign case studies. As discussed, *Tooled mechanical items* are counted within the number of *Mechanical parts* for all relevant activities, which excludes those related to tooling. It is important to note that glue, sealant, and grease is only counted as one *Standard part* each regardless of the number of times it is applied.

All case studies achieved a reduction in the *Total number of items*, with the lowest being case studies 1 and 7 at 66.7%, and the highest being case study 2 at 92.9% - a reduction of 13 items. The *Total number of parts* were also reduced by all case studies, with the highest achieved by case study 4 at 95.8% - a reduction of 23 parts. All relevant case studies resulted in a reduction in the number of *Mechanical items* and *Mechanical parts* down to 1. This did not include case study 7 which had only 1 in the unconsolidated design. The highest reduction in *Mechanical items* was achieved by case study

5 at 80%, a reduction of 4 items. Case study 4 however also achieved the highest reduction of *Mechanical parts* at 83.3%, a reduction of 5 parts.

Only three case studies had *Tooled mechanical items* and *Tooled mechanical parts*, and all were eliminated (100% reduction) for the consolidated design. This indicates that all tooling related costs would be eliminated through PC enabled by AM. Five of the case studies also achieved a 100% reduction in the number of *Standard parts*, however case studies 1 and 6 still required fasteners for assembling out of scope components.

Table 10: Results of the redesign case studies in terms of a reduction in the number of units from the unconsolidated to consolidated design

Redesign case studies		**1**	**2**	**3**	**4**	**5**	**6**	**7**
Total number of items	Unconsolidated	6	14	11	8	7	7	3
	Consolidated	2	1	1	1	1	2	1
	% reduction	66.7%	92.9%	90.9%	87.5%	85.7%	71.43%	66.7%
Total number of parts	Unconsolidated	12	20	20	24	9	16	3
	Consolidated	5	1	1	1	1	2	1
	% reduction	58.3%	95.0%	95.0%	95.8%	88.9%	87.50%	66.7%
Mechanical items	Unconsolidated	3	3	4	3	5	2	1
	Consolidated	1	1	1	1	1	1	1
	% reduction	66.7%	66.7%	75.0%	66.7%	80.0%	50.00%	0.0%
Mechanical parts	Unconsolidated	3	4	4	6	5	2	1
	Consolidated	1	1	1	1	1	1	1
	% reduction	66.7%	75.0%	75.0%	83.3%	80.0%	50.00%	0.0%
Tooled mechanical items	Unconsolidated	2	0	0	2	0	0	1
	Consolidated	0	0	0	0	0	0	0
	% reduction	100%	n/a	n/a	100%	n/a	n/a	100%
Tooled mechanical parts	Unconsolidated	2	0	0	4	0	0	1
	Consolidated	0	0	0	0	0	0	0
	% reduction	100%	n/a	n/a	100%	n/a	n/a	100%
Standard parts	Unconsolidated	9	16	16	18	4	14	2
	Consolidated	4	0	0	0	0	1	0
	% reduction	55.6%	100%	100%	100%	100%	92.86%	100.%

4.2 Potential cost savings from PC for the host company

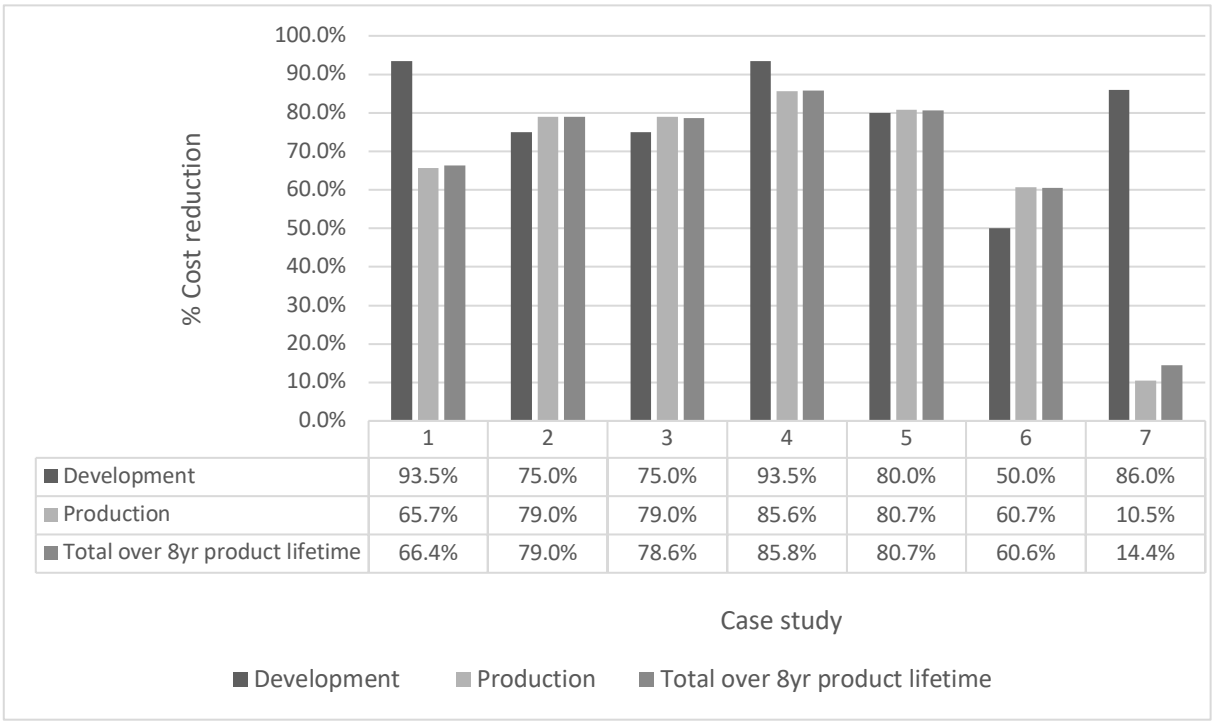
This chapter summarises the results of the PC cost model trial in terms of the potential impact on costs for the host company. Firstly, the results from the model based on the consolidation achieved by each redesign case study will be presented to evaluate the impact on *Development*, *Production*, and total

costs over an 8-yr production lifetime. The costs savings were calculated using data for the cost elements provided by or calculated with the host company. Though real parameters were used, the cost savings are presented as percentages throughout this section to maintain confidentiality.

To provide some insight to the cost savings shown for each cost element, their percentage contribution to total costs is also calculated, as well as the most influential part type consolidation. To capture the potential differences in manufacturing costs for each design, the *Mechanical part manufacture* cost was then be varied as described in section 3.3.2.1 to assess what increase could be absorbed by savings in other cost elements.

4.2.1 Potential impact of PC on Development, Production, and total costs for each redesign case study

Figure 58 shows the results of each redesign case study in terms of the percentage cost saving achieved for *Development*, *Production*, and total costs *(C_{PC})* by the consolidated design assuming an 8-year production life *(PL)*. All these case studies showed a potential *Development* cost saving of between 50% and 93.5%. The highest were case studies 1 and 4, and the lowest was case study 6. The potential *Production* cost saving varied more significantly between 10.5% and 85.6%.



	1	2	3	4	5	6	7
Development	93.5%	75.0%	75.0%	93.5%	80.0%	50.0%	86.0%
Production	65.7%	79.0%	79.0%	85.6%	80.7%	60.7%	10.5%
Total over 8yr product lifetime	66.4%	79.0%	78.6%	85.8%	80.7%	60.6%	14.4%

Figure 58: Cost saving achieved through PC for each redesign case study for Development, Production, and total costs

Interestingly, case studies 1 and 7 both achieve a high *Development* cost saving, but far lower *Production* cost saving and correspondingly low potential total cost saving. For case studies 2-6, there is little difference between potential *Development* and *Production* cost savings, but the total cost saving is closer to those achieved for *Production* costs. This indicated that *Production* cost elements had a much larger contribution to total costs than *Development* cost elements.

4.2.2 Contribution of cost elements to Development, Production, and total costs

To more accurately determine which cost element was the biggest contributor, Table 11 shows the percentage cost savings for each cost element and lifecycle stage as a total from all 7 redesign case studies, and the percentage contribution of each of the elements to *Development*, *Production*, and total costs. The total cost saving form all the case studies was used in this analysis rather than calculating the median or mean, as it is most likely an adopting organisation would apply AM to as many suitable cases as possible in order to get the most advantages. As percentages are used rather than actual costs in this research, these can be applied across multiple cases.

Table 11: Percentage cost saving as a sum of the costs calculated for all the redesign case studies, and contribution of each cost element to Development, Production, and total costs

Cost element	Percentage cost saving	Contribution to lifecycle stage costs	Contribution to total costs
(a) Design	68.18%	13.41%	0.30%
(b) Tolerance analysis	68.18%	1.56%	0.03%
(c) Technical drawings	72%	0.65%	0.01%
(d) Drawing reviews	68.18%	1.63%	0.04%
(e) Source prototypes	68.18%	0.34%	0.01%
(f) Order prototype	68.18%	5.79%	0.13%
(g) Manufacture prototype	68.18%	7.63%	0.17%
(h) Deliver prototype	68.18%	1.85%	0.04%
(i) Source tooling	100%	0.29%	0.01%
(j) Tooling design & analysis	100%	11.92%	0.27%
(k) Tooling manufacture	100%	54.92%	1.23%
Development costs	**86.74%**	**100%**	**2.23%**
(l) Order production	69.21%	8.28%	8.10%
(m) Deliver production	69.21%	3.31%	3.23%
(n) Book in	69.21%	0.16%	0.16%
(o) Tool setting	100%	1.00%	0.97%
(p) Mechanical part manufacture	69.21%	67.74%	66.23%
(q) Kit production	69.21%	0.30%	0.29%
(r) Standard part manufacture	89.98%	12.08%	11.81%
(s) Assembly	85.47%	7.13%	6.97%
Production costs	**72.43%**	**100%**	**97.77%**
Total costs (8yr production life)	**72.70%**	**n/a**	**100%**

Firstly, it is noteworthy that all tool-related costs (cost elements *i, j, k, o*) were eliminated (100% saving), as expected from the 100% reduction in *Tooled mechanical items* and *Tooled mechanical parts*. Though fine-pitch threads are required for case study 6, these can be adequately produced by clamping the part in position by hand. Tooling-related costs were the only cost elements to be eliminated by all case studies. The next largest cost saving was *Standard part manufacture* (89.98% reduction) followed by *Assembly* (85.47% reduction). The remaining cost elements showed a saving of between 68.18% and 72%. The potential *Development* and *Production* cost saving was 86.74% and 72.43% respectively, and 72.70% total cost saving assuming an 8-year production life.

For *Development* costs, *Tool Manufacture* was the biggest contributor (54.92%) followed by *Design* (13.41%) and *Tool Design and Analysis* (11.92%). Collectively, the tool-related cost elements (*i, j, and k*) accounted for 67.13% of the potential *Development* cost saving. *Component design* (*a, b, c, d*) accounted for 17.25% and *Prototyping* (*e, f, g, h*) was 15.61%. Within *Production* costs, *Mechanical part manufacture* was by far the biggest contributor at 67.74%, followed by *Standard part manufacture* (12.08%), *Order production* (8.28%), and *Assembly* (7.13%). The contribution of each cost element and lifecycle stage to total costs showed that *Production* costs have a significantly larger contribution than *Development* at 97.77%.

4.2.3 Correlation analysis - determining the most influential part type consolidation on potential Production cost reductions

Figure 59 shows a simplified linear model of the percentage *Production* cost saving against the percentage consolidation achieved by each of the seven redesign case studies, for *Mechanical parts, Standard parts*, and *Total number of parts*. Using AM processes to manufacture the consolidated design eliminated the need for tooling. Consolidation of *Tooled mechanical parts* would therefore tell us little about the impact of PC on costs, and is more relevant to the general characteristic of a manufacturing process.

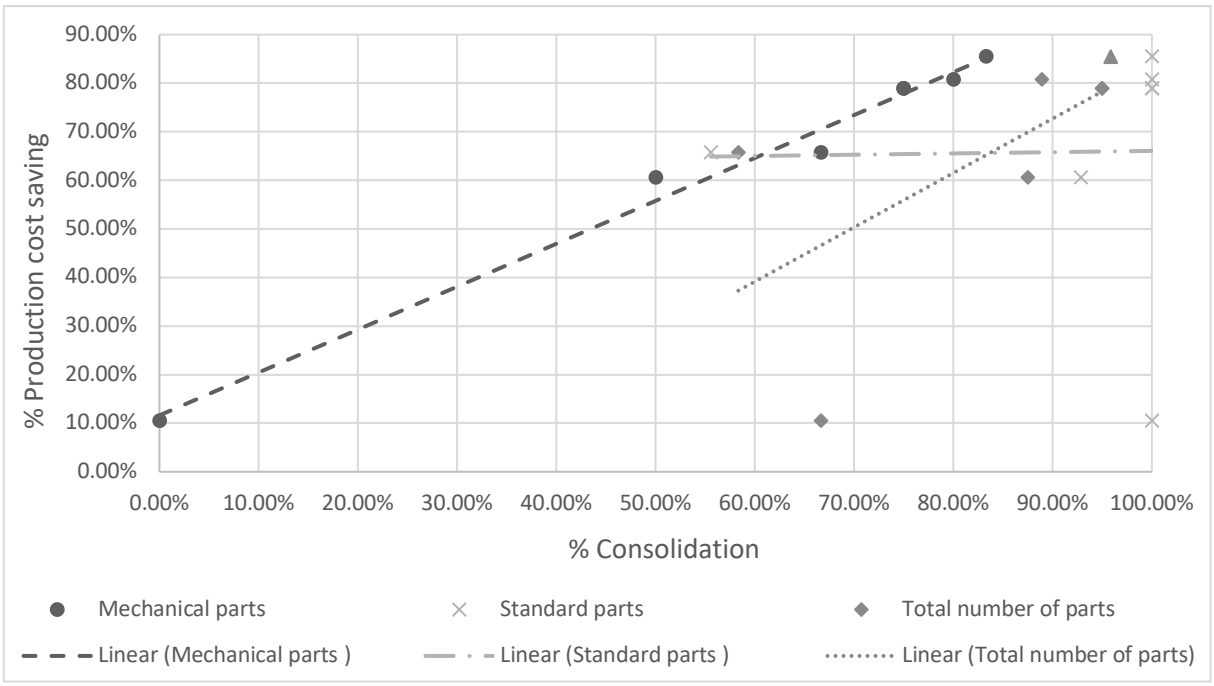


Figure 59: Simplified linear model of percentage Production cost saving against percentage consolidation achieved by each redesign case study for each part type

From the linear regression and R-squared values in Table 12, the results indicate higher cost savings can be achieved with significant consolidation of the *Total number of parts*. However, an R-squared value of 0.425 indicates that the model for *Total number of parts* does not explain the data as well as for the consolidation of *Mechanical parts*, which has an R-squared value of 0.987. The potential *Production* cost impact resulting from PC should therefore be predicted using Y = 0.883x + 0.116, based on the percentage consolidation of *Mechanical parts* only.

Table 12: linear equation and R-squared values for each part type

Part type	Linear equation y = *m*x + *c*	R-squared
Mechanical	Y = 0.883x + 0.116	0.987
Standard	Y = 0.027x + 0.634	0.0003
Total number of parts	Y = 1.118x – 0.279	0.425

4.2.4 Varying Mechanical part manufacturing cost and its impact on Production cost savings

This section presents the results of varying the *Mechanical part manufacture* cost (*p*) for the consolidated design to determine what potential increase in process costs (for example from using AM) could be absorbed by other cost savings. Using equation *IPC'* defined in chapter 3.3.2.1, p_C was

varied at 50%, 100%, 200%, 300%, and 400% of the cost of p_{UC}. *Development* costs were not included as these were not affected by *Mechanical part manufacture* cost.

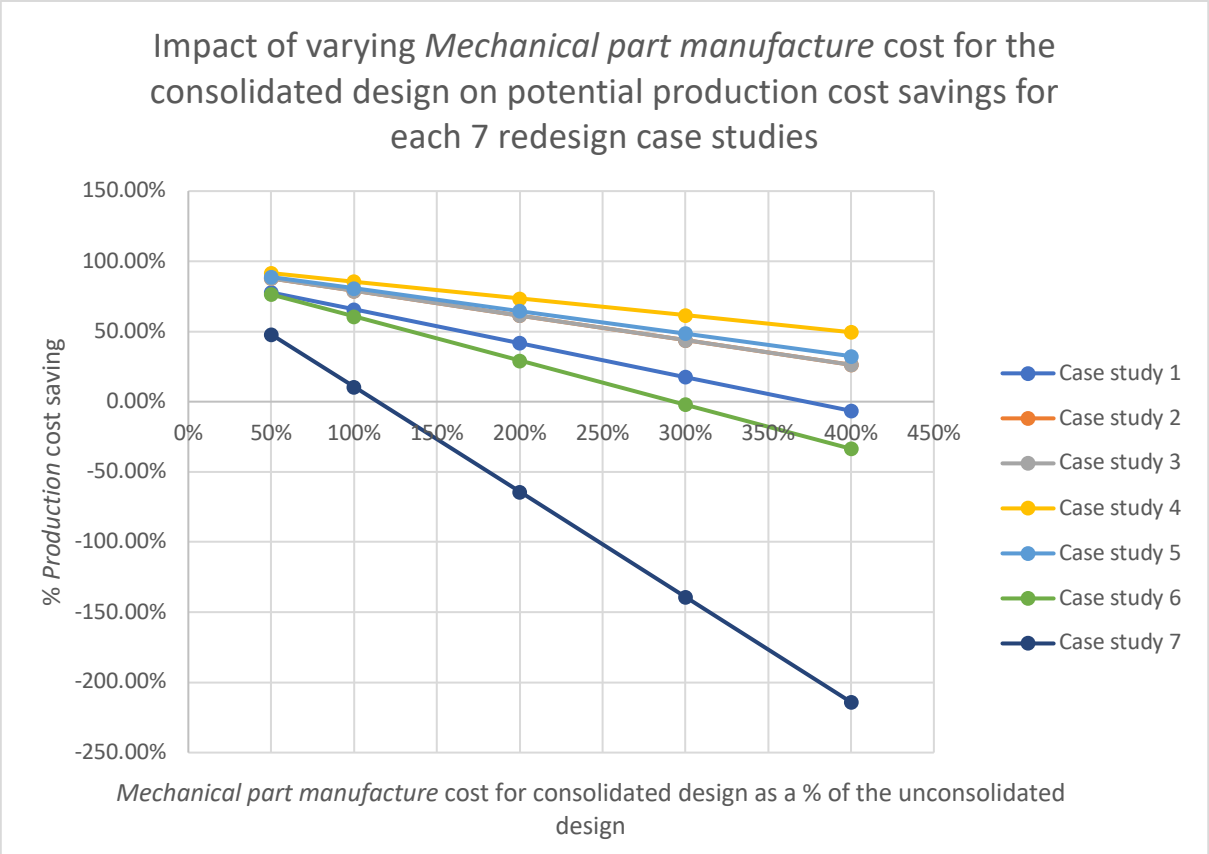


Figure 60 Linear regression of impact on percentage Production cost saving from increases in Mechanical part manufacture cost for each seven redesign case studies, calculated as a percentage of the cost for the unconsolidated design

Figure 60 shows the linear regression of the impact on percentage *Production* cost saving for each of the seven redesign case studies. You can see from this that most case studies would achieve a cost saving or breakeven up to 300%, except for case study 7 which shows an increase in *Production* costs at just over 100%. Case studies 1 and 6 also show a *Production* cost increase at a consolidated design manufacturing cost between 300% and 400% of the unconsolidated design.

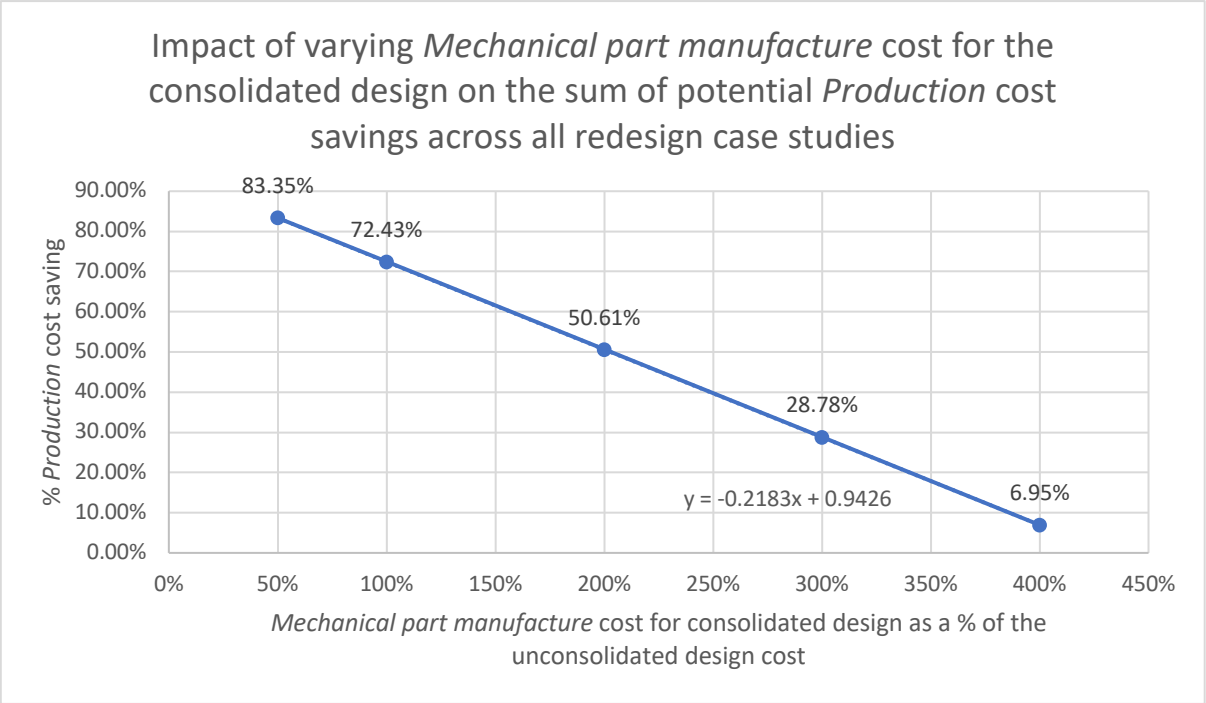


Figure 61 Linear regression of impact on percentage Production cost saving from increases in Mechanical part manufacture using the sum of costs from all case studies

Figure 61 shows a linear regression for the impact of varying manufacturing costs on the total percentage *Production* cost saving calculated as a sum of all the redesign case study costs. It shows that a Pro*duction* cost saving of 6.95% is still achieved even when the manufacturing costs for the consolidated designs are 400% of those for the unconsolidated designs. To determine the maximum increase in P_C which could be absorbed by other cost savings from PC, a simplified linear model of percentage *Production* cost saving at varying p_C values was calculated:

$$y = -0.2183x + 0.9426$$

The maximum increase in manufacturing costs for the consolidated designs which would indicate no cost saving or increase in costs (y <= 0%) would therefore be at 431.8% of p_{UC}.

4.3 PC cost model utilisation tool

The PC cost model was developed into an Excel-based tool by the researcher to improve utilisation by making it easily adaptable for other adopting organisations to use during their own pre-installation phase of AM implementation. The adaptable parameters defined in the methodology section were grouped together, and divided into columns for the unconsolidated design and consolidated design. An example of parameters that might be defined for the model are shown in Table 13. The exact

parameters used for the host company are confidential. Initial analyses in this research for the host company used the same time and cost parameters for each design, except for *Mechanical part manufacture* cost. However, this tool enables future research and adopting organisations to adapt each parameter for each design extremely easily.

Each cost element was defined on a separate row as an equation as summarised in Table 5 and Table 6 within section 3.2.3. Excel enables each equation to link directly to the parameters table, so that different analysis can be performed very quickly and easily. Figure 62 shows an example of the tool in use using the example parameters, and Figure 63 shows an example with varying *Mechanical part manufacture* cost for each design. A separate page can be used for the results of the PC redesign case studies in terms of the number of *Items* and *Parts*, shown in Table 14 and linked directly to different pages and analyses.

Table 13 Example parameters defined for the PC cost model Excel tool

Parameters

Unit	Unconsolidated	Consolidated
Mechanical item	4	2
Mechanical part	6	2
Prototypes per Mechanical item	2	2
Tooled mechanical items	2	0
Tooled mechanical parts	4	0
Yearly production volume	1000	1000
Standard parts	12	0
Total number of parts	18	2
Time (hrs)		
Design	10.00	10.00
Technical drawings	1.50	1.50
Tolerance analysis	1.00	1.00
Drawings review	2.5	2.5
Source prototypes	0.25	0.25
Source tooling	2	2
Book in	0.0040	0.0040
Kit production	0.0060	0.0060
Assembly time	0.01	0.01
Cost (£)		
Order prototype	£20.00	£20.00
Manufacture prototype	£75.00	£75.00
Deliver prototype	£20.00	£20.00
Tooling d&a	£2,500.00	£2,500.00
Tooling manufacture	£8,000.00	£8,000.00
Tool setting	£1.00	£1.00
Order production	£5.00	£5.00
Deliver production	£0.50	£0.50
Mechanical part manufacture	£10.00	£10.00
Standard part manufacture	£0.60	£0.60
Labour cost rate 1	£30.00	£30.00
Labour cost rate 2	£20.00	£20.00

	C	D	E	F	G	H	I	J	K	L
1	**Potential impact of PC on costs**									
2	**Cost Element**	**Unit**	**Unconcosolidated**	**Consolidated**	**Cost saving**			**Parameters**		
3	Design	Mechanical item	=K4*K13*K33	£600.00	£600.00	50.00%		**Unit**	**Unconsolidated**	**Consolidated**
4	Technical drawing	Mechanical item	£180.00	£90.00	£90.00	50.00%		*Mechanical item*	4	2
5	Tolerance analysis	Mechanical part	£180.00	£60.00	£120.00	66.67%		*Mechanical part*	6	2
6	Drawing reviews	Mechanical item	£300.00	£150.00	£150.00	50.00%		*Prototypes per Mechanical item*	2	2
7	Source prototypes	Mechanical item	£30.00	£15.00	£15.00	50.00%		*Tooled mechanical items*	2	0
8	Order prototypes	Prototypes per Mechanical item	£160.00	£80.00	£80.00	50.00%		*Tooled mechanical parts*	4	0
9	Manufacture prototypes	Prototypes per Mechanical item	£600.00	£300.00	£300.00	50.00%		*Yearly production volume*	1000	1000
10	Deliver prototypes	Prototypes per Mechanical item	£160.00	£80.00	£80.00	50.00%		*Standard parts*	12	0
11	Source tooling	Tooled mechanical item	£120.00	£0.00	£120.00	100.00%		*Total number of parts*	18	2
12	Tooling design and analysis	Tooled mechanical item	£5,000.00	£0.00	£5,000.00	100.00%		**Time (hrs)**		
13	Tool manufacture	Tooled mechanical item	£16,000.00	£0.00	£16,000.00	100.00%		*Design*	10.00	10.00
14	**DEVELOPMENT COSTS**	**TOTAL**	**£23,930.00**	**£1,375.00**	**£22,555.00**	**94.3%**		*Technical drawings*	1.50	1.50
15	Order production	Mechanical part	£30,000.00	£10,000.00	£20,000.00	66.67%		*Tolerance analysis*	1.00	1.00
16	Deliver production	Mechanical part	£3,000.00	£1,000.00	£2,000.00	66.67%		*Drawings review*	2.5	2.5
17	Book in	Mechanical part	£480.00	£160.00	£320.00	66.67%		*Source prototypes*	0.25	0.25
18	Tool setting	Tooled mechanical part	£4,000.00	£0.00	£4,000.00	100.00%		*Source tooling*	2	2
19	Mechanical part manufacture	Mechanical part	£60,000.00	£20,000.00	£40,000.00	66.67%		*Book in*	0.0040	0.0040
20	Standard part manufacture	Standard part	£7,200.00	£0.00	£7,200.00	100.00%		*Kit production*	0.0060	0.0060
21	Kit production	Mechanical part	£720.00	£240.00	£480.00	66.67%		*Assembly time*	0.01	0.01
22	Assemble	Total number of parts	£3,600.00	£400.00	£3,200.00	88.89%		**Cost (£)**		
23	**YEARLY PRODUCTION COSTS**	**TOTAL**	**£109,000.00**	**£31,800.00**	**£77,200.00**	**70.8%**		*Order prototype*	£20.00	£20.00
24	**PRODUCT LIFETIME COSTS (8yrs)**	**TOTAL**	**£895,930.00**	**£255,775.00**	**£640,155.00**	**71.5%**		*Manufacture prototype*	£75.00	£75.00
25								*Deliver prototype*	£20.00	£20.00
26								*Tooling d&a*	£2,500.00	£2,500.00
27								*Tooling manufacture*	£8,000.00	£8,000.00
28								*Tool setting*	£1.00	£1.00
29								*Order production*	£5.00	£5.00
30								*Deliver production*	£0.50	£0.50
31								*Mechanical part manufacture*	£10.00	£10.00
32								*Standard part manufacture*	£0.60	£0.60
33								*Labour cost rate 1*	£30.00	£30.00
34								*Labour cost rate 2*	£20.00	£20.00

Figure 62: Example results of the PC cost model calculated with the Excel tool, showing the equation defined with Excel for Design

	C	D	E	F	G	H	I	J	K	L
1	**Potential impact of PC on costs**									
2	**Cost Element**	**Unit**	**Unconcosolidated**	**Consolidated**	**Cost saving**			**Parameters**		
3	Design	Mechanical item	£1,200.00	£600.00	£600.00	50.00%		**Unit**	**Unconsolidated**	**Consolidated**
4	Technical drawing	Mechanical item	£180.00	£90.00	£90.00	50.00%		*Mechanical item*	4	2
5	Tolerance analysis	Mechanical part	£180.00	£60.00	£120.00	66.67%		*Mechanical part*	6	2
6	Drawing reviews	Mechanical item	£300.00	£150.00	£150.00	50.00%		*Prototypes per Mechanical item*	2	2
7	Source prototypes	Mechanical item	£30.00	£15.00	£15.00	50.00%		*Tooled mechanical items*	2	0
8	Order prototypes	Prototypes per Mechanical item	£160.00	£80.00	£80.00	50.00%		*Tooled mechanical parts*	4	0
9	Manufacture prototypes	Prototypes per Mechanical item	£600.00	£300.00	£300.00	50.00%		*Yearly production volume*	1000	1000
10	Deliver prototypes	Prototypes per Mechanical item	£160.00	£80.00	£80.00	50.00%		*Standard parts*	12	0
11	Source tooling	Tooled mechanical item	£120.00	£0.00	£120.00	100.00%		*Total number of parts*	18	2
12	Tooling design and analysis	Tooled mechanical item	£5,000.00	£0.00	£5,000.00	100.00%		**Time (hrs)**		
13	Tool manufacture	Tooled mechanical item	£16,000.00	£0.00	£16,000.00	100.00%		*Design*	10.00	10.00
14	**DEVELOPMENT COSTS**	**TOTAL**	**£23,930.00**	**£1,375.00**	**£22,555.00**	**94.3%**		*Technical drawings*	1.50	1.50
15	Order production	Mechanical part	£30,000.00	£10,000.00	£20,000.00	66.67%		*Tolerance analysis*	1.00	1.00
16	Deliver production	Mechanical part	£3,000.00	£1,000.00	£2,000.00	66.67%		*Drawings review*	2.5	2.5
17	Book in	Mechanical part	£480.00	£160.00	£320.00	66.67%		*Source prototypes*	0.25	0.25
18	Tool setting	Tooled mechanical part	£4,000.00	£0.00	£4,000.00	100.00%		*Source tooling*	2	2
19	Mechanical part manufacture	Mechanical part	£60,000.00	£40,000.00	£20,000.00	33.33%		*Book in*	0.0040	0.0040
20	Standard part manufacture	Standard part	£7,200.00	£0.00	£7,200.00	100.00%		*Kit production*	0.0060	0.0060
21	Kit production	Mechanical part	£720.00	£240.00	£480.00	66.67%		*Assembly time*	0.01	0.01
22	Assemble	Total number of parts	£3,600.00	£400.00	£3,200.00	88.89%		**Cost (£)**		
23	**YEARLY PRODUCTION COSTS**	**TOTAL**	**£109,000.00**	**£51,800.00**	**£57,200.00**	**52.5%**		*Order prototype*	£20.00	£20.00
24	**PRODUCT LIFETIME COSTS (8yrs)**	**TOTAL**	**£895,930.00**	**£415,775.00**	**£480,155.00**	**53.6%**		*Manufacture prototype*	£75.00	£75.00
25								*Deliver prototype*	£20.00	£20.00
26								*Tooling d&a*	£2,500.00	£2,500.00
27								*Tooling manufacture*	£8,000.00	£8,000.00
28								*Tool setting*	£1.00	£1.00
29								*Order production*	£5.00	£5.00
30								*Deliver production*	£0.50	£0.50
31								*Mechanical part manufacture*	£10.00	£20.00
32								*Standard part manufacture*	£0.60	£0.60
33								*Labour cost rate 1*	£30.00	£30.00
34								*Labour cost rate 2*	£20.00	£20.00

Figure 63: Example results of the PC cost model calculated within the Excel tool using different costs for Mechanical part manufacture

Table 14 PC redesign case study results in terms of the number of Items and Parts input into the Excel tool

	Case study													
	1 Lens and filter mount		2 Double fold optic mount		3 Feed funnel		4 Folded air duct		5 Cover door		6 Fibre optic mount		7 Thermal insulator	
Unit	Unconsolidated	Cons	Unconsolidated	Cons	Unconsolidated	Cons	Unconsolidated	Cons	Unconsolidated	Cons	Unconsolidated	Cons	Unconsolidated	Cons
Mechanical items	3	1	4	1	4	1	3	1	5	1	2	1	1	1
Mechanical parts	3	1	4	1	4	1	6	1	5	1	2	1	1	1
Prototypes per mechanical item	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Tooled mechanical items	2	0	0	0	0	0	2	0	0	0	0	0	1	0
Tooled mechanical parts	2	0	0	0	0	0	4	0	0	0	0	0	1	0
Yearly production volume *(confidential)*														
Standard parts	9	4	16	0	16	0	18	0	4	0	14	1	2	0
Total number of parts	12	5	20	1	20	1	24	1	9	1	16	2	3	1

5 Discussion

This chapter will discuss the research results in three main sections. The first section covers the impact of the redesign case studies in terms of designing for PC, the benefits and limitations of the redesign approach used, and utilising the design freedom of AM to consolidate or eliminate *Mechanical parts* and *Standard parts*. The implications on DFMA rules defined by Boothroyd (1987) are also summarised, showing that AM can consolidate parts that need to move bodily to other parts already assembled, and enable assembly of out of scope components using elastic force and snap-fit connections.

The next section discusses the potential impact of PC on costs for the host company in terms of the most significant cost element and part type, and the impact of varying manufacturing costs and production volumes.

The third section discusses the implications of the research for the pre-installation phase of AM implementation. The cost model enables organisations to consider the benefits of PC within the justification stage, basing the analysis on empirical evidence with regards to the potential for PC within their own products via the redesign case studies. The use of the redesign case studies as implementation pilot projects is also discussed.

The fourth section outlines the development of a practical framework based on the methodology followed for this research and the Excel-based utilisation tool, to help future adopting organisations adapt the cost model to help justify AM adoption based on PC.

5.1 Designing for PC

5.1.1 Benefits and limitations of the PC re-design approach

Though not a focus of this research, a general re-design approach based on several methodologies and existing experience was outlined in chapter 3.3.1.1. First, it was important to identify the components which were out of scope and could not be consolidated, but would still need to be assembled. The material requirements could be defined based on the functional requirements and remaining in scope components. Suitable AM processes were then identified based primarily on the material requirements.

As the focus was on the general ability of AM to manufacture consolidated assemblies, and the model does not differentiate between different AM processes, it was not important to identify all potentially suitable processes for each design. Identifying a process early on did help the researcher consider

potentially influential process characteristics that might impact the consolidated design, such as support structure and post-processing requirements, as suggested by Ponche et al. (2012), Klahn et al. (2015), and Schmelzle et al. (2015).

Case studies 1 and 6 for example were both complex designs in terms of internal and overhanging geometries and features, and were manufactured using PBF in Aluminium meaning they required support structures. It was important to think about what orientation it might be built in, and consider access to support structures that might be needed. The remaining case studies were manufactured using support-free processes, and were simpler to design with fewer process limitations and characteristics to consider. Case study 3 was relatively complex, as it had an integrated hinge for the lid of the funnel. It was important that the tolerances were correct for the process so the hinge did not fuse together during the build, and that an additional hole was included to make powder removal and dying easier. It was also important that the integrated cable clip in case study 7 had big enough wall thicknesses to cope with anisotropic mechanical properties induced from the layer-wise build method and build orientation.

Prototypes were used for all the case studies throughout the redesign process to ensure the form and function were correct. Some initially used the prototyping technology that the host company had in-house, even though it was not the intended manufacturing process. This helped to reduce lead times associated with external prototyping. However, the nature of the designs meant that is was critical to get prototypes manufactured in the chosen process as early as possible due to the implications of the material and mechanical properties. A benefit of AM processes is the lack of tooling and ability to manufacture prototypes throughout the development process in the intended process for production parts, improving the testing process and final design. A part requiring metal for example would need a functional prototype in metal as early as possible to properly understand material performance, and the different processes and even machines can vary significantly in their limitations. See section 2.1.7 for more detailed information on the limitations of AM processes.

Overall, the re-design approach used for the PC case studies helped provide a structured approach for consolidating existing assemblies resulting in a reduction in part count. However, it does not differentiate between manufacturing processes which will have varying considerations in terms of design capability, post-processing requirements, and mechanical properties. Ultimately due to time constraints and limited experience with individual processes, the researcher relied on the manufacturing suppliers to define the most suitable orientation and post-processing procedures, and took on board any feedback they might have with regards to minor design improvements. Process

specific design guidelines could be added to this general approach, helping designers consider unique characteristics and therefore improve the end design.

5.1.2 Utilising design freedom of AM to consolidate mechanical and standard parts

It was recognised early on during the redesign of the case studies that *Mechanical parts* could be consolidated by recognising design features which were based on traditional process characteristics and limitations. For example, for assemblies with machined parts such as case studies 3, 5, ad 6; tool access could be ignored and undercuts and organic forms more easily manufactured. For assemblies with injection moulded (tooled) parts such as case studies 1, 4, and 7; split lines, rounds, and drafts could be ignored and undercuts manufactured with ease.

Assembly of the original unconsolidated *Mechanical parts* had also required *Standard parts* for assemblage such as fasteners and glue. Case studies 1 and 4 required a complex assembly process with glue and fasteners to assemble the parts into a lens mount and air duct respectively. Multiple screws were also needed for case study 6 for assembling the *Mechanical parts* of the mount. Other *Standard parts* were also required to ensure the assemblies performed the required function. O-rings and sealant were required for case study 4 to ensure the separate air duct parts were air tight. Springs and dowel pins were needed for case study 6 to enable the assembly to be repositionable. By consolidating the *Mechanical parts*, these *Standard parts* were no longer required.

5.1.3 Implications of case studies on DFMA rules

As discussed in the literature review, reducing part count has long been a focus of DFMA rules with regards to traditional manufacturing processes such as machining and injection moulding (Boothroyd, 1996, Prakash et al., 2014, Kuo et al., 2001). Three main questions were defined by Boothroyd (1987) to help reduce part count:

1. *Does this part move bodily with respect to all other parts already assembled?*
2. *Does it have to be a different material?*
3. *Does it need to be separate so that other parts can be assembled/disassembled?*

However, these were based on the limitations of traditional manufacturing processes and correlation between design complexity and manufacturing costs. As seen in the redesign case studies, the result for the host company using traditional processes had been products with multiple sub-assemblies with high part count and often complicated assembly. Without the same limitations or correlation between

complexity and cost, it has been suggested by Schmelzle et al. (2015) and Tang et al. (2016) that the DFMA rules defined above are no longer valid for AM. However, there is currently very little case study research for proper investigation and analysis. The next two sections will investigate the implications of the redesign case studies on the questions above.

5.1.3.1 Consolidating parts which need to move bodily with respect to other parts

Case study 3 integrated a hinge and used a snap-fit locking mechanism to replace the need for magnets in the consolidated design. This also eliminated the screws required to assemble those parts together (Figure 64). Case study 6 took advantage of undercuts and varying wall thickness to create a consolidated repositionable fibre optic mount based on flexure hinges in two orientations for pitch and yaw deflection (Figure 65). This eliminated the need for separate springs and screws previously used to assemble the two *Mechanical parts* and still allow pitch and yaw deflection.



Figure 64: Integrated hinge and snap-fit locking mechanisms resulting in the consolidation and elimination of Standard parts for redesign case study 3

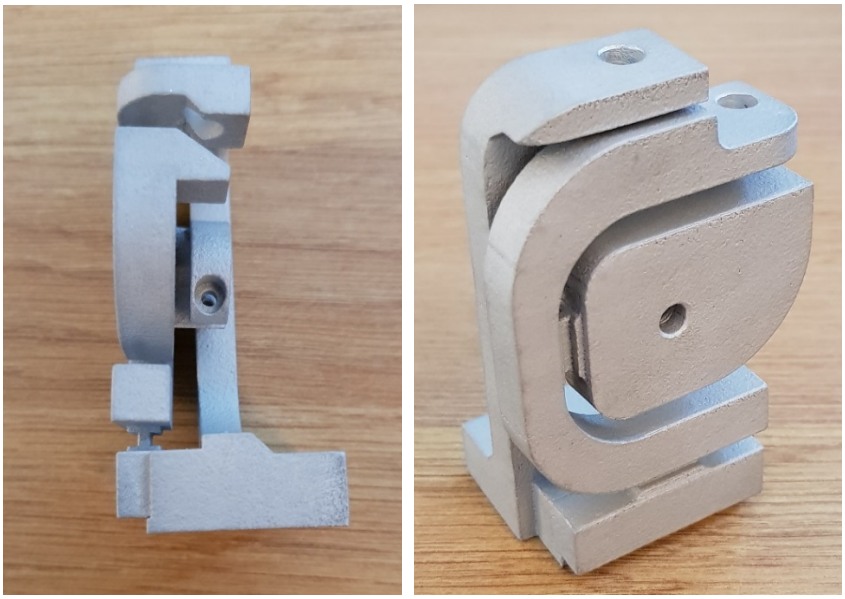


Figure 65: Varying wall thickness for pitch and yaw flexure hinges - redesign case study 6

These case studies imply that rule number 1 as defined by Boothroyd (1987) is no longer valid for AM processes, confirming the assessments by Schmelzle et al. (2015) and Tang et al. (2016) that AM can build parts that need to *"move bodily with respect to all other parts already assembled"*. In fact, in the case of case study 7, it is the fibre optic cable which is then assembled to the consolidated part which is designed to move bodily with respect to the top-level assembly. It would be interesting to investigate if further sub-assemblies could be consolidated and if the need for repositionable parts is eliminated by reducing tolerance accumulation. Sub-assemblies could become part of a consolidated top-level assembly, significantly reducing the bill-of-materials for products.

5.1.3.2 Consolidating parts of different materials

The original assemblies had multiple parts often made of different materials. *Mechanical parts* that were previously different materials were consolidated in redesign case studies 1 and 4. For case study 1, the function of the metal bracket to ground the assembly was consolidated into the main consolidated part (effectively eliminating the bracket rather than consolidating it), by making the consolidated mount out of metal (Figure 66). The tooled parts would previously have been either not possible or not cost effective to produce using traditional metal processes. Case study 4 consolidated two polymer fins that were required for directing air flow with the injection moulded components of the air duct (Figure 67). This particularly complex geometry was manufactured using powder bed fusion in PA12, with careful attention paid to removal of unsintered build material in the internal channels.

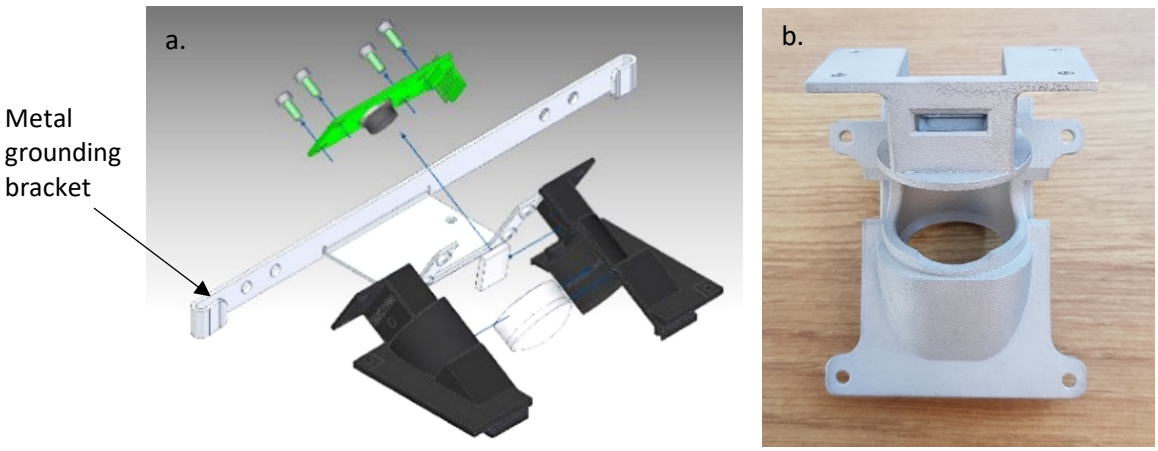


Figure 66 Consolidating parts of different materials – elimination of metal grounding bracket used for redesign case study 1: a) original unconsolidated design with metal grounding bracket b) consolidated design made using metal to make the whole part conductible

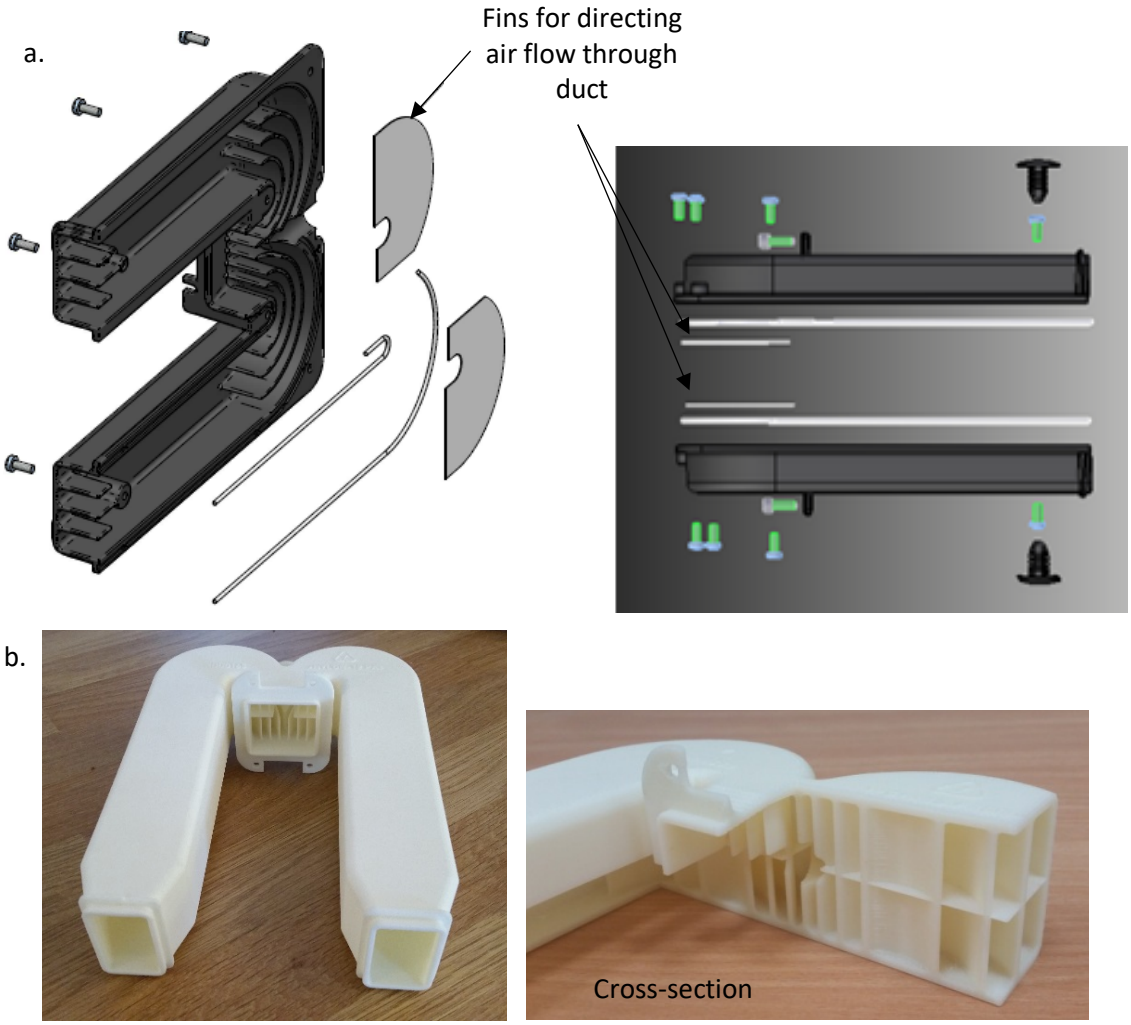


Figure 67 Consolidating parts of different materials – two fins for directing air flow in redesign case study 4: a) original unconsolidated design with separate fins b) consolidated design and cross-section showing the fin geometry

5.1.3.3 Consolidating parts required for assembly/disassembly of other parts

Some case studies, though consolidated, still had out of scope components requiring assembly. As per Boothroyd (1987)'s question number 3 , this would originally have meant separate parts were required as in case study 2 and 3. For case study 2, *Mechanical parts* and O-rings were needed to secure and protect the optics, and screws for fastening these parts in place. Case study 3 required assembly of a window which needed screws for fixing it to the lid. The design freedom of AM meant that elastic force and snap fit connections (Figure 68 and Figure 69 respectively) could be designed to reduce parts needed for assemblage and fastening, as identified by Gibson et al. (2010a) and Grzesiak et al. (2011).

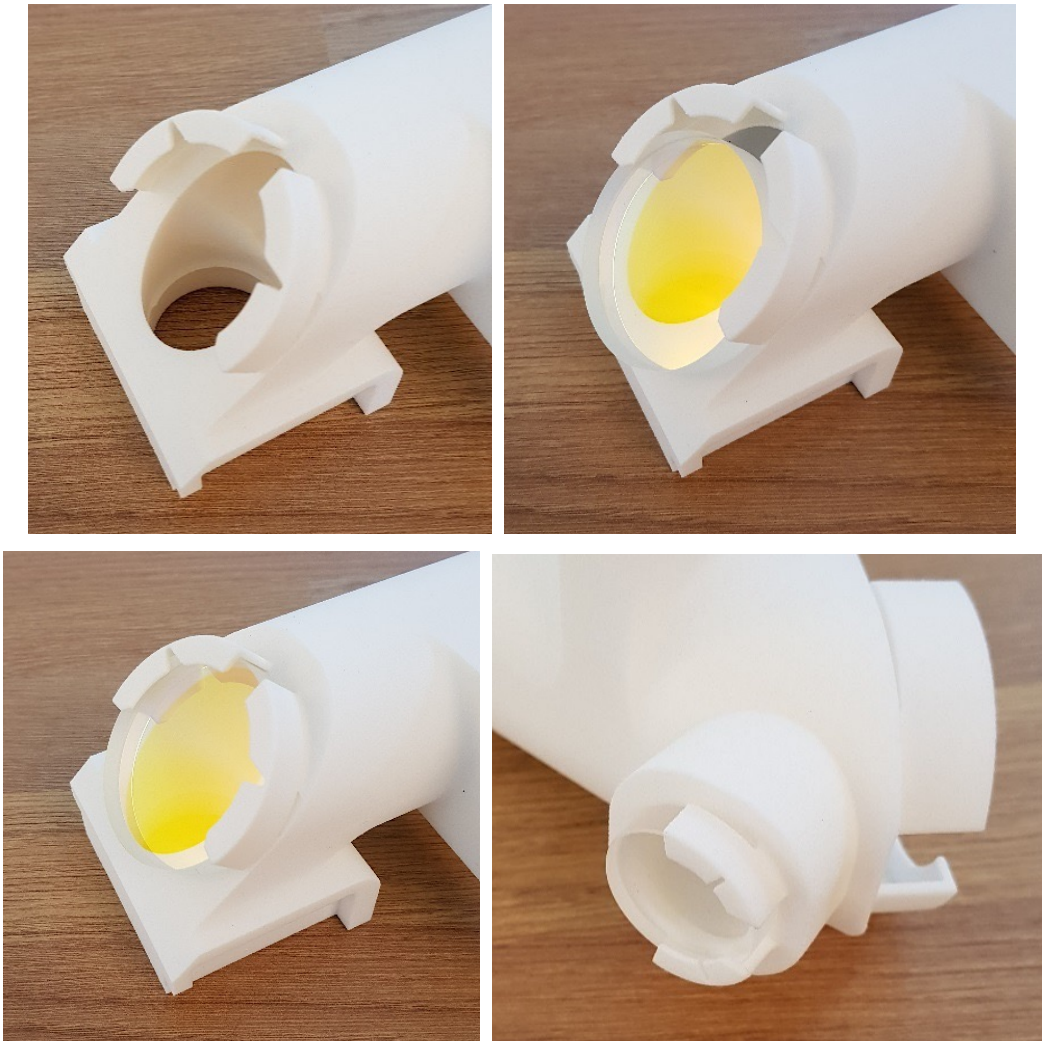


Figure 68: Assembly of optics for redesign case study 2 using elastic force connections, helping to eliminate the need to O-rings and separate mechanical parts to hold them securely in place



Figure 69: Snap-fit connections on redesign case study 3 for assembling a window

Case study 1 originally took advantage of the split line requirement for injection moulded components to assemble the lens and filter at the same time as fixing the two halves together with glue. By consolidating these halves, assembly of the lens and filter had to be accommodated by designing slots into the mount (Figure 70). The assembly did however still require four screws to assemble the PCB to the conductive mount to ensure sufficient contact (Figure 71). A screw was also required to assemble the fibre optic cable for redesign case study 6 (Figure 72), though significant consolidation of *Mechanical parts* and *Standard parts* was still achieved by utilising the design freedom of AM.

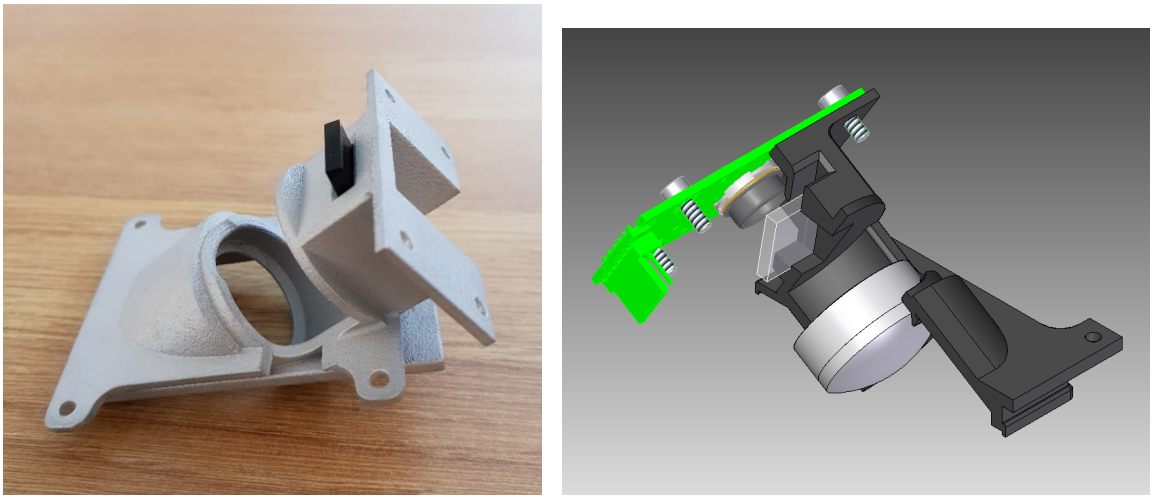


Figure 70: Assembly of blue obscuration filter and lens for redesign case study 1 using slots

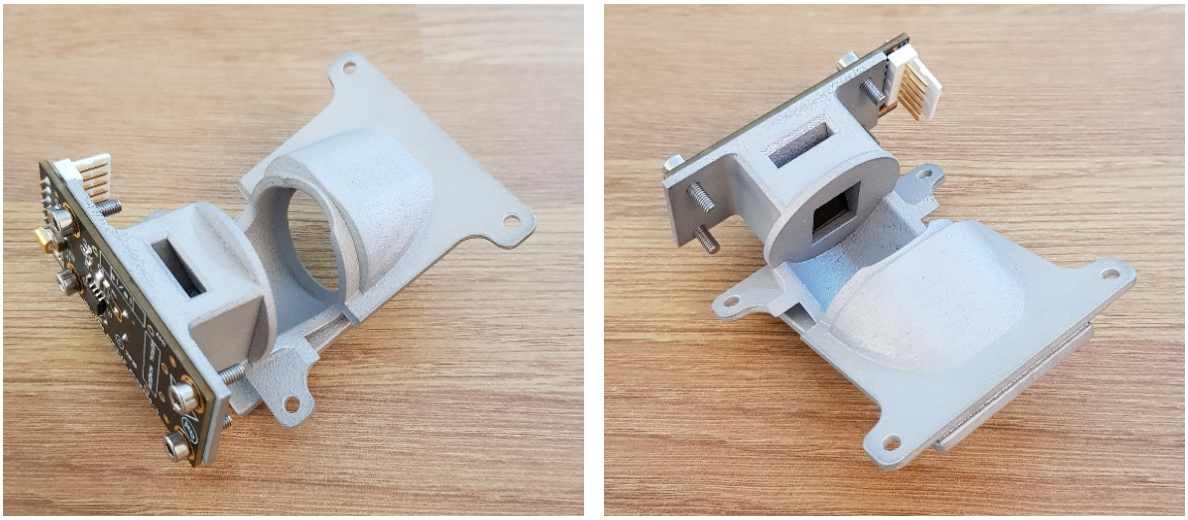


Figure 71: Assembly of PCB using fasteners for case study 1

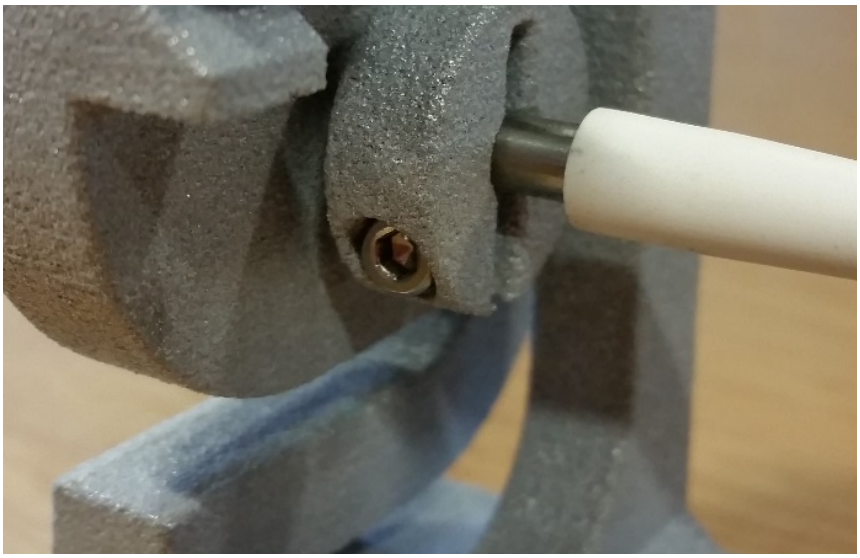


Figure 72: Assembly of fibre optic cable using 1 fastener for case study 6

These redesign case studies back up claims by Schmelzle et al. (2015) and Tang et al. (2016) that AM enables parts to be consolidated even if other separate components must be assembled. However, the fact that screws were still required for two case studies which were both manufactured using Aluminium PBF suggests that this capability might depend on the manufacturing process. As most AM design methodologies also specify steps for optimisation such as Rodrigue and Rivette (2010), Yang et al. (2015b), Cardona (2015), and Liu (2016); it might also be that further optimisation of the consolidated designs could result in the elimination of separate fasteners for case studies 1 and 6.

5.2 The impact of PC on costs

5.2.1 Most significant cost elements and lifecycle stage

As expected from the nature of AM processes that require no tooling, the case studies showed that all tooling-related cost elements were eliminated within both *Development* and *Production* stages. The contribution of each cost element to the lifecycle stage costs show that eliminating *Tool manufacture* would halve the *Development* costs for the host company. This analysis looks at the total cost saving achieved across the case studies, assuming these results would then be extrapolated to top-level assemblies. The percentages are based on the redesign case studies chosen for the host company, where only three of the case studies featured *Tooled mechanical parts.* The researcher would suggest that the ratio of redesign case studies requiring tooling for the unconsolidated design to those that do not, should reflect the overall product range so that results can be more accurately extrapolated. More redesign case studies could also be performed to further investigate this relationship.

Mechanical part manufacture was the biggest contributor to *Production* costs, followed by *Standard part manufacture*, *Order production*, and *Assembly*. The results confirm Weller et al. (2015) that a reduction in assembly can reduce marginal costs of assembly intensive production, and reflects the results of Atzeni et al. (2010) who calculated that assembly had a smaller impact on costs than the manufacturing process. However, due to the complexity of the host company products and required assembly processes, the researcher was surprised that *Assembly* did not have a bigger impact on costs. This could be due to the relatively small production volumes of the host company. The results also indicate that further analysis into the effects of varying *Mechanical part manufacture* costs is justified, to better understand how different manufacturing processes might impact potential cost savings.

Calculating the percentage contribution of each lifecycle stage to total costs found that *Production* was by the far the biggest contributor over *Development*. This differs from Lindemann et al. (2013) who found that the *Design and Development* phase was the biggest contributor. However, their research represented theoretical aspects without properly accounting for PC, and their model was based on the aerospace industry. A significant part of their *Development* cost was also due to the optimisation process which was not part of the redesign approach in this research.

As discussed, efforts to optimise consolidated designs could further consolidate *Standard parts* required for case studies 1 and 6. Optimisation could also be applied to other sub-assemblies to further consolidate a top-level assembly, potentially significantly increasing cost savings as indicated by Weller et al. (2015). Though the model does not reflect the costs of the redesign process, the time and resources required for optimisation should be considered for both the redesign case studies

performed within the pre-installation phase of implementation, and the *Development* costs for the unconsolidated design within the cost model itself.

5.2.2 Most influential part type consolidation for reducing costs

The results clearly showed that reducing part count could result in significant potential cost savings. However, the model is based on cost elements multiplied by different numbers of part type (unit) characterised as *Mechanical*, *Tooled mechanical*, *Standard*, and *Total number of items* and *parts*. A better understanding of the most significant part type on potential cost savings through consolidation could be gained by looking at the linear regressions and the r-squared value for each pat type presented in section 4.2.3. This would help to both identify suitable products or assemblies, and more accurately predict the potential cost saving.

Production costs were the focus of this analysis as it had already been determined that these had the biggest contribution to total costs. As *Production* costs are only concerned with *Parts, Items* were not investigated. *Tooled mechanical parts* were not included in this analysis as the elimination of these part types was due to the inherent nature of AM processes, not necessarily through PC and so would tell us little about the relationship of this part type and potential cost savings.

Though it appeared that *Production* cost savings were more sensitive to the *Total number of parts*, the number of *Mechanical parts* had a significantly better R-squared value of 0.987 or 98%. This was because the *Total number of parts* included *Standard parts*, which had a smaller contribution to cost savings. The host company would therefore focus on consolidating *Mechanical parts* in their products to yield the greatest cost savings through the implementation of AM. Although case study 7 achieved a relatively high percentage reduction of *Total number of parts*, it showed a very small potential *Production* cost saving of only 10.5%. This can now be explained by the fact that it had only 1 *Mechanical part* in the unconsolidated design, and therefore very little consolidation potential. The highest cost saving calculated was 85.6% for case study 4 which reduced the number of *Mechanical parts* in the assembly by 83.3% (5 *Mechanical parts)*.

As already discussed in chapter 5.1.2, *Mechanical parts* could be consolidated using AM when they have been split due to manufacturing limitations, including those that need to move bodily to each other, were of different materials, and to assemble other out of scope components. Consolidating the *Mechanical parts* then results in the elimination of *Standard parts* that were no longer required for assemblage.

5.2.3 Impact of varying Mechanical part manufacturing cost on potential cost savings through PC

The analyses already performed gives a good indication of the significance of the potential cost savings from PC and shows *Mechanical part manufacture* cost *(*cost element *p)* to be the biggest contributor to *Production* costs. Current research shows AM to be most cost-effective for low volume production – which is the category that best describes the host company in this research. They also have a high machine and material cost associated to them, labour intensive pre- and post-processing requirements, and a small build volume and slow build speed which reduces machine productivity and increases costs (Bhattacharjya et al., 2014, Oettmeier and Hofmann, 2016, Berman, 2012, Khajavi et al., 2014, Weller et al., 2015). However, research suggests that developments to AM processes will increase productivity and reduce overall manufacturing costs. A reduction (50% of the unconsolidated design) and more significant increase (400%) in manufacturing costs for the consolidated design were therefore used in calculations to understand the implication of current and future scenarios on *Production* cost savings.

The impact on *Production* cost savings looking at each individual redesign case study shows that as would be expected, consolidated designs which achieved the greatest reduction in the number of *Mechanical parts* showed a smaller reduction in savings with increases in manufacturing cost. I.e. the more *Mechanical parts* consolidated, the smaller the impact of their manufacturing cost on *Production* cost savings. This can be expected as it has already been established that *Mechanical part manufacture* is the biggest contributor, and this cost is a product of the number of *Mechanical parts*.

When looking at the total *Production* cost savings as a sum from all the case studies at the different *Mechanical part manufacture* costs, the linear regression (y = -0.2183x + 0.9426) shows a breakeven in *Production* costs when p_C = 431.8%*p_{UC}. This implies that the host company could adopt AM to manufacture consolidated designs at a 331.8% increase in manufacturing costs and not incur any overall cost penalties. If the *Mechanical part manufacture* cost for the unconsolidated design was £20 for example, the consolidated design could cost up to £86.36. £46 for the consolidated design would be 230% of £20, which using the linear regression y = -0.2183x + 0.9426 would indicate a *Production* cost saving of 44.05%. The calculations could be used by the adopting organisation to inform decisions about further implementation and future product development.

These figures show that a fairly significant increase in manufacturing costs for the consolidated design could be absorbed by wider cost savings. The linear regression is based on the sum of *Production* cost savings from all the redesign case studies. More redesign case studies would provide a more accurate assessment of what cost saving could be achieved if AM was adopted across a wide range of products.

Manufacturing costs for the consolidated designs were also not gathered in this research due to optimisation being out of scope of the redesign process, meaning they could not be used to validate these assessments. However, an increase in manufacturing costs of over 300% could be considered significant, and offers a different perspective to current research on the cost effectiveness of AM versus traditional processes.

It is also important to remember the wider context of this cost model being a pre-installation tool, and should be used early on in the adoption process of new technologies. It should also be adapted to the adopting organisation to reflect their own business model, which could calculate a smaller contribution of manufacturing costs to *Production* costs, altering the impact of manufacturing costs for the consolidated design on potential cost savings. More detailed investigations should be performed including further cost analyses when decisions such as the overall production strategy and use or implementation of a particular technology have been made. A more thorough discussion of the impact of this research on the pre-installation phase of AM implementation can be found in section 5.3. The model can be easily adapted in any phase of implementation, to consider both larger and smaller manufacturing cost ranges than those currently investigated.

5.2.3.1 Impact of production volumes

The low correlation between production volumes and manufacturing costs for AM processes does mean that production volumes of the adopting organisation should be considered when calculating different scenarios and interpreting results. With AM, there is lower amortisation of costs over the production volume, meaning they are considered most cost-effective for low volumes. Calculating scenarios with a reduction in manufacturing costs for the consolidated design could therefore be justified if production volumes are particularly low or the part/assembly is customised.

Organisations with very high production volumes might find it difficult to justify scenarios with a similar or small increase in manufacturing costs for the consolidated design. However as previously discussed, future process and design optimisation development will help to reduce AM costs and make them more cost-effective for higher volumes. The rate that AM processes are developing implies the need to consider these factors, but also makes it difficult to make any predictions.

The impact on percentage cost saving calculated by the PC cost model would not be impacted by production volumes assuming these are the same for both designs. This research does not investigate the impact of PC on product functionality, performance, and robustness; and therefore, whether the consolidated design might increase sales (and production volumes).

The actual cost savings achieved through PC in the case presented in this research (which are not disclosed for confidentiality reasons) would be greatly impacted by production volumes, as these cost elements are a product of yearly production volumes and production life. Products with the highest production volumes and largest reduction in the number of *Mechanical parts* would show the greatest *Production* cost savings. More considerable cost savings could also be achieved however if the manufacturing cost for the consolidated design is similar or less than that of the unconsolidated design, or if the production volumes of the consolidated design were more than the unconsolidated design.

The results in this research are only indicative of characteristics (and production volumes) unique to the adopting organisation making it difficult to appreciate the impact of production volumes on the individual cost elements. Whilst higher production volumes of a different organisation might indicate more storage, transportation, and assembly resulting in higher costs; it might also lower traditional manufacturing process costs. The cost elements themselves may also be different depending on the business model and supply chain of the adopting organisation. This research was limited to the adopting organisation, but the model should be adapted and tested for different organisation with their own redesign case studies, to compare to the results in this research. A framework for justifying AM adoption based on PC is presented in section 5.4 which focuses on ensuring the cost model results are accurate and relevant to the adopting organisation.

5.3 Implications for the pre-installation phase of AM implementation

5.3.1 Considering the impact of PC on costs within justification

As discussed, research into the implementation of AMTs gained momentum when organisations where finding they were not delivering them with the required or expected benefits and being dubbed failures in terms of quality, flexibility, and reliability (Chen and Small, 1994, Lewis and Boyer, 2002). The pre-installation phase of implementation defined by Voss (1988) was found to be the most critical for success at it ensured a robust decision-making and planning process (Udoka and Nazemetz, 1990, Hayes and Jaikumar, 1991, Laosirihongthong et al., 2003, Chen and Small, 1994, Shang and Sueyoshi, 1995, Small and Yasin, 1997).

Within pre-installation is the need for a hybrid justification approach to quantify all tangible and intangible benefits of the technology to increase implementation success (Small and Chen, 1995, Small, 2006, Banakar and Tahriri, 2010, Chan et al., 2001, Borges and Tan, 2007, Kreng et al., 2011, Aravindan and Punniyamoorthy, 2002). However, these adoption principles have not been

appropriately transferred to AM indicating that organisations are not performing a robust implementation process and are therefore reducing potential success. This research expands on the framework defined by Deradjat and Minshall (2015), which includes a pre-installation phase but has been developed based on implementing AM for mass customisation for the dental industry and does not expand on justification methods.

The cost model presented in this research provides organisations with a tool to help justify AM adoption during the pre-installation phase of AM implementation based on potential cost savings from PC within *Development* and *Production*. The results reflect Achillas et al. (2014) who suggested that PC would reduce overall production costs to capture more value and increase profitability. The significant potential cost savings from PC also indicate that the cost-effectiveness of AM versus traditional processes could be greatly impacted by wider lifecycle stages, which current analyses such as Khajavi et al. (2014), Atzeni et al. (2010) and Atzeni and Salmi (2012) do not account for. The analyses in this research show that for the host company, an increase in manufacturing costs for the consolidated design compared to the unconsolidated design of 331.8% could be absorbed by wider cost savings. This suggests that conclusions drawn with regards to both cost-effective production volumes and cost-effective supply chains for AM must be redefined, based on analyses which include wider lifecycle stages in their calculations in order to appropriately account for the impact of PC on costs.

5.3.2 The benefits of the PC redesign case studies

The redesign case studies were embedded within the single company case study approach used to develop the cost model, as discussed in section 3.1.1. Their purpose was to enable the researcher to investigate PC in isolation and the cost model trial to be based on empirical evidence. The aim of the case studies was to cover a range of functional requirements and applications that reflect the product range of the host company.

When applying the PC results and observations to top level assemblies, the host company could assume that further significant consolidation is possible. This could be both in terms of reducing part count in sub-assemblies, and even consolidating multiple sub-assemblies into one. If no out of scope components are needed, a sub-assembly can be consolidated to become a single part. Products would have considerably reduced part count, which based on this research would result in significant cost savings assuming the manufacturing cost for the consolidated design using AM is similar to that of the unconsolidated design.

However, this potential for top-level product consolidation is difficult to confirm without a redesign case study featuring an entire product. It could be assumed that companies with simpler products have less consolidation potential, and would therefore find it far more difficult to justify AM adoption based on cost savings from reducing part count. If PC results in more robust products and lower lead times however, customers may be willing to pay more, impacting the value chain of an organisation's business model (Rayna and Striukova, 2016, Khajavi et al., 2014).

5.3.2.1 Using the redesign case studies as implementation pilot projects

As well as providing empirical data for the units of the consolidated design, the case studies could also serve as implementation pilot projects for the adopting organisation. Identified within AMT implementation research as a valid pre-installation technique, pilot projects can help provide an opportunity to learn about new manufacturing technologies and identify required processes and training requirements prior to installation (Lewis and Boyer, 2002). Subsequently, this can help with the cultural issues surrounding AMT implementation, helping to increase implementation success (Lewis and Boyer, 2002, Udoka and Nazemetz, 1990, Saberi and Yusuff, 2011, O'Connor et al., 1990).

Generally, powder bed fusion was defined as the most suitable process in this research due to both the materials and mechanical properties. However, processes that could have been used to manufacture these designs are not limited to those defined in this research. The main aim of the case studies was to identify the inherent capability of AM processes to manufacture consolidated assemblies, and to understand what impact that consolidation might have on costs. The process of certifying the manufacture of the consolidated designs using AM might be a far more complex process which was beyond the scope of this research. However, they can still be used as a learning exercise to familiarise the organisation with new manufacturing processes, and could be used to further validate different processes for production.

5.4 Developing a practical framework to help justify AM adoption based on PC

The researcher has discussed throughout this thesis the need for both the model and the parameters of the model to be adapted to the unique processes, activities, and products of the adopting organisation to increase the relevance of results. A practical framework for justifying AM adoption based on PC is therefore proposed, based on the methodology used in this research described in chapter 3.

The first step would be to adapt the current cost model elements to reflect the business model and processes of the adopting organisation, focusing on activities that might be impacted by the number of parts within an assembly. For example, drawings reviews may not be performed so these could be removed. Supply chains might be considerably different, perhaps with on demand production which would drastically alter the cost elements associated with delivery and storage of *Mechanical parts* prior to assembly. These would also need to be defined as a direct cost or cost rate multiplied by the number of *Units* relevant to that activity.

The next step would be to identify the potential for PC based on redesign case studies performed within the adopting organisation, such as were performed for the host company in this research. The re-design approach defined in chapter 3.3.1.1 could be used to help with the redesign process. Step 3 requires the cost and time parameters to be defined. The potential impact of PC on costs in terms of a cost saving can then be calculated in step 4 using the Excel-based utilisation tool described in chapter 3.3.3.

The final step is to perform more in-depth analysis into using AM processes for production of consolidated designs. This additional step was included in order to overcome some of the main limitations of this research imposed by the reduction in scope with regards to the case studies. Whilst they currently help indicate a potential reduction in part count through very basic consolidation and agglomeration of existing parts, they have not been optimised for performance or production. This means they currently do not help verify critical properties such as part life, accuracy, and robustness that would enable the company to use a particular AM process for production. Post-processing activities may also be required such as secondary machining which will impact costs and the supply chain. Existing AM cost models as described in section 2.3.2.1 can be used to calculate part cost once suitable processes have been chosen and consolidated designs have been optimised to reduce build time and material use and improve performance. A more thorough discussion of the impact of *Mechanical part manufacturing* costs on *Production* cost savings can be found in section 5.2.3. Figure 73 summarises this five-step practical framework.



Figure 73: Development of research methodology into a practical framework to be used by other adopting organisations to justify AM adoption based on PC

Existing AM implementation and evaluation frameworks such as Mellor (2014), Deradjat and Minshall (2015), Achillas et al. (2014), and Oettmeier and Hofmann (2016) as well as research into the implementation of advanced manufacturing processes could be used to inform subsequent implementation steps and identify other adoption related costs. The factors defined in their frameworks could be used to develop a robust implementation plan which might impact the cost elements developed in this research for the consolidated design, and consequently the potential cost savings.

The researcher suggests there may be a need to continuously adapt the cost model throughout the implementation process when new knowledge and data becomes available and a plan can be more clearly defined. As discussed, the redesign case studies could also be used as implementation pilot projects to investigate production process costs, supply chain, and other wider lifecycle implications for specific cases so that the model can reflect more realistic instances. However this research is only concerned with its use as a pre-installation tool and cannot be used in isolation to justify AM implementation, as existing research is clear on the need for a range of methods to be used during the justification stage (Small and Chen, 1995, Small, 2006, Banakar and Tahriri, 2010, Chan et al., 2001, Borges and Tan, 2007, Kreng et al., 2011, Aravindan and Punniyamoorthy, 2002).

5.4.1 Benefits of the Excel-based utilisation tool

The development of the cost model into an Excel tool enabled the parameters of the model to be adapted quickly and easily by the researcher. More analyses could be performed, helping to develop a better understanding about the potential impacts AM and relationship with the existing business model and processes.

Developing the model into an easily accessible and adaptable tool should help to increase the utilisation of this research for the benefit of wider AM adoption within different industries. It also provided a platform for storing and displaying all the data and calculations on one database, that could then be made available to independent (or further) inspection (Baxter and Jack, 2008). The parameters for each design could be easily varied for example to explore other impacts of AM, such as mass customisation and decentralised on-demand production.

6 Conclusions

Initially a literature review was conducted to identify and evaluate existing knowledge on PC enabled by AM processes, the implementation of new manufacturing technology, and how the potential benefits of PC can be properly considered when making decisions about AM adoption. Two main knowledge gaps were subsequently identified. Firstly, there had been very limited transfer of the considerable research around AMT implementation to AM, particularly with regards to justifying adoption for a robust pre-installation phase. Secondly, despite PC being described as one of the major benefits of AM, current process cost models did not account for wider lifecycle stages making it impossible to quantify the impact of PC on costs. Four research objectives were defined to help provide empirical evidence and further insight into these knowledge gaps:

A. Develop a cost model to quantify potential cost savings from PC, for organisations to use during the pre-installation phase of AM implementation
B. Identify the potential for PC using redesign case studies so the model analyses can be based on empirical evidence
C. Evaluate the significance of the cost impact of PC within AM adoption
D. Develop a practical framework for adapting and applying the PC cost model to help justify AM adoption based on PC

This chapter will conclude with limitations of the research and suggestions for further work.

6.1 Develop a cost model to quantify potential cost savings from PC, for organisations to use during the pre-installation phase of AM implementation

A cost model was developed in section 3.2 to provide a method to help justify AM adoption based on potential cost savings from PC, for use during the pre-installation phase of AM implementation. The model was based on the host company (Malvern Instruments) who design and manufacture precision instruments for material and biophysical characterisation. A single company case study research approach was used due to the nature of the funding of the research by the host company. Embedded redesign case studies were used to investigate PC within the host companies products, to calculate potential cost savings from PC using empirical evidence.

The model was based on research by Lindemann et al. (2013), but only incorporated the *Development* and *Production* stages of a products lifecycle in order to reduce the scope of this research. It incorporated a range of cost elements based on activities which might be impacted by the number of parts within an assembly, which were defined as a direct cost or cost rate. Terminology to appropriately describe a reduction in part count relevant to the cost element was defined in section

3.2.2. These were described as units, which were sub-divided into *Item* or *Part* depending on the type of activity and whether it was impacted by production volumes and the quantity of that part within the assembly. There were then three types of *Item* and *Part* defined – *Mechanical*, *Tooled mechanical*, and *Standard.*

Results from the model can be used as part of the justification process, which is critical for robust decision-making and planning. The research expands on the AM implementation frameworks defined by Mellor (2014), Deradjat and Minshall (2015), Oettmeier and Hofmann (2016); which either currently do not specify or do not expand on a pre-installation phase, assuming the business case (and justification for adoption) has already been defined. A detailed review of existing literature on the implementation of advanced manufacturing technologies, and AM implementation and evaluation frameworks and cost models can be found in section 2.3.

6.2 Identify the potential for PC using redesign case studies so the model analyses can be based on empirical evidence

The second objective was met using embedded redesign case studies performed within the host company. The purpose of these case studies was to investigate PC in isolation, and to base the units of the cost model on empirical evidence with regards to a realistic potential reduction in part count for a consolidated versus unconsolidated assembly. They were chosen to reflect a range of applications and complexity in terms of the number of parts in the unconsolidated design, across the host company's products.

The redesign approach shown in Figure 43 in section 3.3.1.1 helped to consolidate the assemblies by identifying parts that could be consolidated and eliminated. The potential for consolidation was present both when sub-assemblies had been split up due to manufacturing constraints, and for assembly of other components such as optics and PCBs. This helped identify the implications of AM on traditional DFMA rules discussed in chapter 5.1.3. They show that AM can consolidate parts that needed to move bodily with respect to other parts, were of different materials, and were required for assembly/disassembly of other components. The resulting designs required significantly less assembly than the unconsolidated designs.

The PC redesign case studies are presented in section 4.1. They showed significant potential for PC for the host company, with up to a 95.8% (23 parts) reduction in the *Total number of parts,* 83.3% (5 parts) reduction in the number of *Mechanical parts*, and 100% (up to 18 parts) reduction in the number of *Standard parts*. This degree of consolidation was made possible by the design freedom

offered by AM processes. It should also be remembered that these case studies are also low level sub-assemblies of very complex products, and a considerably higher reduction in the number of parts could be achieved for the top-level assemblies if multiple sub-assemblies were consolidated.

6.3 Evaluate the significance of the cost impact of PC within AM adoption

The third objective was met using the redesign case studies and host company data to trial the cost model and calculate potential cost savings from PC for the host company, presented in section 0. The actual costs and cost savings calculated cannot be disclosed for confidentiality reasons. The highest total cost saving calculated for a case study was 85.8%, the highest *Development* cost saving was 93.5%, and the highest *Production* cost saving was 85.6%. Further analyses looking at the sum of costs across all the case studies showed that *Production* had a significantly larger impact on total cost savings than *Development* costs at 97.77%, and within that *Mechanical part manufacture* was the biggest contributor to *Production* costs at 67.74%.

A simplified linear model of *Production* cost savings against percentage consolidation for each case study was used to identify which part type was most influential on cost savings. The analysis showed that potential cost savings from PC can be predicted based on the percentage consolidation of *Mechanical parts.* This implies that the host company should focus on reducing the number of *Mechanical parts* in their assemblies to achieve the greatest cost savings from PC.

The cost model equation was developed in section 3.3.2.1 to allow for varying manufacturing costs to consider a range of current and future scenarios. It showed that a significant increase of 331.8% could be absorbed by wider cost savings. The more *Mechanical parts* that are consolidated, the lower the impact of manufacturing costs on potential cost savings. Different organisations may also find their manufacturing costs have a smaller contribution to total costs than calculated for the host company in this case, which would change the impact of manufacturing costs on cost savings.

When considering AM, the researcher often encounters perceptions within industry that it is *"too expensive"* compared to traditional manufacturing processes. This appears to be widely backed up by AM cost research, finding it only cost-effective for low volume production and centralised spare part supply chains (see section 2.3.2.1). However, this research indicates that even if the manufacturing costs for the consolidated designs using AM are significantly more than those for the unconsolidated design utilising traditional processes, AM-enabled PC could still be cost-effective when the wider product lifecycle is also taken in to account.

This could have considerable implications for an organisation's pre-installation phase of AM implementation – and more specifically the justification for adoption - by reducing the risk associated with high manufacturing costs. Section 5.3 presents a discussion on the implications of the research results on the pre-installation phase of AM implementation.

The redesign case studies presented in this research show significant potential for consolidation and a correspondingly high potential cost saving for the host company. The results indicate that the potential cost savings from PC would be a significant part of the host company's justification of AM adoption. It helps to answer questions with regards to "why" they should employ AM, and provide the financial justification for further funding and allocation of resources. The company will be able to have a more balanced view of the "cost" of AM processes throughout further investigations in suitable production processes and supply chains.

6.4 Develop a practical framework for adapting and applying the PC cost model to help justify AM adoption based on PC

As discussed in section 2.3 of the literature review, research into the implementation of advanced manufacturing processes identified the need for the implementation processes to be unique to the adopting organisation. The cost model developed in this research has been based on the processes, business model, and products of the host company. A structured approach for justifying AM adoption based on PC was therefore developed in chapter 5.4 to improve the utilisation of the cost model and help with further adoption of AM. An additional step was defined for more in-depth production analyses of AM processes and costs using existing AM cost models, due to the impact of manufacturing costs on cost savings calculated within this research.

Based on the methodology followed in this research, it could help organisations to adapt the cost model to their own business model and activities, and define the parameters of the model based on their own data and redesign case studies. Currently this cost model has been developed as a justification tool within the pre-installation stage, meaning decisions on production technologies, supply chain, business model and strategy are unlikely to have been defined. The case studies could serve as implementation pilot projects to investigate process costs, supply chain, and other wider lifecycle implications for specific cases further into the implementation process. AMT implementation research and existing AM implementation and evaluation frameworks such as Mellor (2014), Deradjat and Minshall (2015), Achillas et al. (2014), and Oettmeier and Hofmann (2016) could be used to inform subsequent implementation steps and identify other adoption related costs.

6.5 Limitations and suggestions for further work

The cost model does not take into account other lifecycle stages, such as those defined by Lindemann et al. (2013) as Conception and definition, Installation, Usage and Maintenance, and Disposal. As discussed in the literature review for example, PC can reduce the tolerance accumulation of assemblies helping to improve robustness and product quality. This might help reduce maintenance requirements and improve customer satisfaction, resulting in both reduced costs and increased sales. Reducing part count could also simplify the spare part supply chain, and both reduce and simplify disassembly requirements at end of life. A reduction in disassembly costs could increase the cost-effectiveness of other more sustainable end of life options such as refurbishment and reuse. Recycling could also become more cost-effective with fewer parts - including *Standard parts* and fasteners - and fewer materials to separate.

AM enabled parts that were different materials to be consolidated where this had no negative impact on function or performance. However, some case studies still required separate parts that were different materials, not only standard parts for assembly purposes but also out of scope parts such as optics and electronics which could not be manufactured using AM processes. The use of multi-material AM processes to achieve PC where parts still need to be of different materials for functionality was not investigated in this research. As discussed, further optimisation of the redesign case studies could enable standard parts required for assembly of out of scope components to be eliminated. Future process and material developments could also enable out of scope components to be manufactured additively, potentially using multi-material processes. This could help increase PC potential significantly, with further cost savings indicated by this research.

However the sustainability of this option must be considered, as difficulties with materials separation as well as potentially poor mechanical properties would impact the suitability of these processes for end production purposes. In the theme of widening our net with regards to what we consider “costs” and “benefits”, the researcher argues that the benefit of multi-material AM processes to achieve PC may not outweigh the environmental cost. When we look at the manufacturing complexity that can be achieved using AM processes, more beneficial research could be to design your required material properties, for example through metamaterials and biomimetic materials. Current research and applications are reviewed in section 2.1.1.1.

Another limitation is that even within the considered *Development* and *Production* stages, a number of ill-structured costs were not included in the final model. This meant that some impacts of PC on *Development* and *Production* costs remain theoretical, as although a cost saving is indicated, it may not have been proven or appropriately quantified. Whilst reducing part count might indicate fewer

design and assembly reviews for example, it is difficult to know how the new design capabilities enabled by AM might impact the time taken to review those designs. Designs may be multi-functional and more complex; but there may also be considerably fewer process limitations to consider. Assembly of sub-assemblies might also still require jigs, but this research only looked at one sub-assembly in a product.

The cost elements and testing of the model are also based on the host company and have not been validated using other organisations. Focusing on one company did enable the researcher to fully embed themselves helping to identify the major restrictions to further AM adoption and successful implementation. However, other organisations particularly in different industries might have varying business models and therefore different cost elements relevant to capturing the impact of reducing part count on costs. Products may also be significantly different, with redesign case studies showing more or less consolidation potential using AM. This would both change the potential cost savings calculated and the contribution of each cost element to those savings. Where manufacturing costs were the biggest contributor for the host company, another organisation might not get the same results. For the host company this meant they needed to understand the impact of both an increase and decrease in manufacturing cost for the consolidated design on potential cost savings to make informed decisions in the future.

Reducing part count has long been a focus of traditional DFMA guidelines to increase efficiency and reduce costs, but has often been restricted due to manufacturing limitations. The cost model developed in this research was not meant to be specific to AM technologies, but seeks to offer a method for considering one of the most significant benefits of AM (PC) during the pre-installation phase of implementation. It calculates potential cost savings from PC based on case studies manufactured using AM but does not consider alternative supply chains to those currently used for traditionally manufactured parts. As discussed in the literature review (section 2.1.5), the main considerations for AM are the impact of decentralising the supply chain, on-demand production, direct fabrication and home fabrication on the ability of organisations to propose, create, deliver, and capture value.

On-demand decentralised production for example could significantly reduce warehousing, transportation, inventory, lead times, and natural resource use (Ashour Pour et al., 2015). Reducing the number of parts and tooling might reduce the number of suppliers and supply chain complexity. However, the relative immaturity of the AM supply chain and quality control could make it both difficult to find and manage external suppliers, and may impact the ability of PC to reduce the risk of fluctuating lead times. Internal production might also require a number of different technologies,

machines, materials, operators, and equipment, which would all need to be managed and properly implemented. Even without decentralising AM production, reducing the number of parts could significantly impact energy consumption throughout the product's lifecycle by reducing transportation, storage, maintenance, repair and assembly requirements; and potentially extend product life by increasing robustness through reduced tolerance accumulation.

Process cost models were also not constructed in this cost model. Although this was to keep the model general to all manufacturing processes to maintain focus on PC, this research confirms Atzeni et al. (2010) and Atzeni and Salmi (2012) that manufacturing costs are still the most significant proportion of total costs. Not only should process cost models therefore be incorporated in the future, they must also be developed to account for any increase in manufacturing and post-processing cost due to higher product complexity. Complex internal voids, re-entrant shapes, and functional articulations could make access to support structures more difficult and so increase post-processing costs. The consolidated form might increase build volume and reduce nesting efficiency, which impacts machine productivity and therefore costs (Bhattacharjya et al., 2014, Oettmeier and Hofmann, 2016, Berman, 2012, Khajavi et al., 2014, Weller et al., 2015). However, future process developments will likely increase build speed, resolution and accuracy, helping reduce AM manufacturing and post-processing costs.

AM process cost models will remain an integral part of implementation and justification decisions. Specifically, future make-or-buy decisions would need to be made, which would subsequently impact the implementation plan and process. The results of this research indicate that conclusions drawn with regards to both cost-effective production volumes and cost-effective supply chains for AM may need to be completely redefined, based on analyses which include wider lifecycle impacts of PC in their calculations.

When focusing on this cost model as a justification tool within pre-installation, it should also be remembered that the model does not reflect the costs of redesigning the case studies, or subsequent implementation activities that might be defined after successful justification and development of a plan. It should therefore not be used to justify transferring production of the redesigned case study assemblies to AM. The case studies only help to evaluate the potential for PC, and justify implementation based on potential cost savings from part count reduction. Though not robust in their consideration of the pre-installation phase or justification requirements, existing AM implementation and evaluation frameworks such as Mellor (2014), Deradjat and Minshall (2015), Achillas et al. (2014), and Oettmeier and Hofmann (2016), are critical for developing the implementation plan, identifying any other adoption related costs, and identifying the requirements

to verify AM for production of parts or products. Other benefits of the technology should also be considered when justifying AM adoption such as mass customisation and weight reduction which are not investigated in this research.

Three main areas for further research for successful implementation of AM have been identified. Firstly, the model should be validated using other organisations, with different business models and products to compare to the results calculated for the host company. Empirical evidence should be gathered to provide more accurate cost and time data for the cost elements of the consolidated design, such as design and drawing time.

Secondly, process cost models should be incorporated to improve the accuracy of results but should only be used for designs which have been optimised. The purpose of the case studies used in this research was to give empirical data on potential part count reduction and quantify this in terms of a cost saving to help justify further implementation and adoption of AM. The proposed practical framework in section 5.4 should be used very early on in the pre-installation phase of implementation, and further investigations would be needed to help justify the use of particular AM processes for production of consolidated parts.

Thirdly, more empirical research is needed to understand and quantify all the impacts of AM on business models and the value chain. Organisations will then have the information, data, and justification needed to develop a robust plan for successful implementation of AM.

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