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HOW SIGNIFICANT IS THE COST IMPACT OF PART CONSOLIDATION WITHIN AM ADOPTION?

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Abstract

Successful implementation of advanced manufacturing technologies requires a robust pre-installation phase involving evaluation and justification of potential benefits. However, despite part consolidation (PC) being described as one of the major benefits of additive manufacturing (AM), there has been very little quantification of its potential impact on costs. This makes it difficult for organisations to consider all the benefits of AM adoption. A case study research approach has been used to develop an empirical cost model based on PC for the development and production stages of a product, which can be adapted by organisations during their own pre-installation stage. The case studies involve re-design of existing sub-assemblies within a laboratory instrument producer, and the resulting cost model has been trialled using empirical data. The results show that AM has the potential to considerably reduce part count by up to 93% and associated costs by up to 85%. The significant cost saving occurs where PC results in the consolidation of numerous components thereby eliminating considerable cost elements.

Introduction and background

Advanced manufacturing technologies have the potential to improve manufacturing operations by reducing costs and increasing flexibility and quality (Oettmeier and Hofmann, 2016, Efstathiades et al., 2002). However, research into implementation gained momentum when organisations were identifying that they were not delivering the required or expected benefits (Chen and Small, 1994), with 50-75% being dubbed failures in terms of flexibility, quality, and reliability (Lewis and Boyer, 2002). Implementation is defined by Voss (1988) as *"the user process that leads to the successful adoption of an innovation of new technology"* and generally follows their 3-phase model of pre-installation, installation and commissioning, and post-commissioning. Implementation success is defined by Udo and Ehie (1996) as *"when set goals and objectives stipulated by the adoption strategy are fully realised"*. Further investigations into implementation failures found that the pre-installation phase 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). Several planning and transfer models have since been developed to try and provide organisations with a structured approach for their pre-installation phase (Chen and Small, 1994, Shang and Sueyoshi, 1995, Small and Yasin, 1997, Efstathiades et al., 2002, Saberi and Yusuff, 2011). Drawing from this research, 3 main stages for pre-installation have been identified (Figure 1): evaluating potential benefits, impacts, and applications; justifying adoption of a technology or portfolio of technologies; and planning the implementation process.

The nature of advanced manufacturing technologies 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). Failure to properly account for all benefits during justification will mean the organisation is not assessing the true performance of the technology (Small and Chen, 1995, Small, 2006). 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). The planning process should then 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).

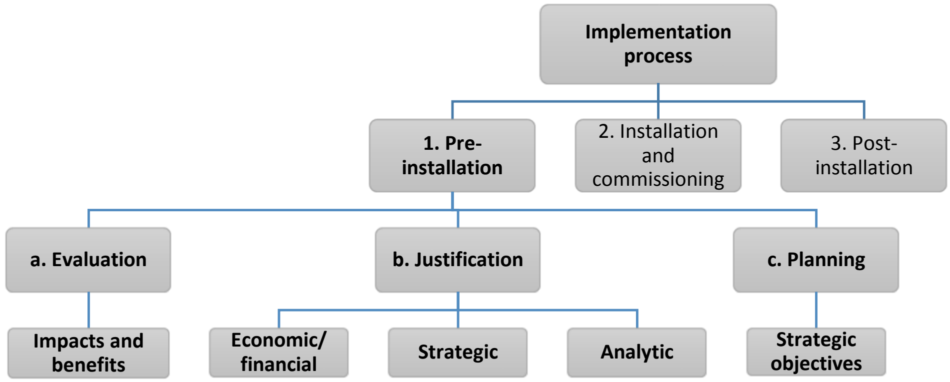


Figure 1 3 stages of pre-installation based on existing advanced manufacturing technology planning and transfer models and research

Though Additive Manufacturing (AM) is considered an advanced manufacturing technology, its layer-wise build method gives it capabilities far beyond traditional manufacturing processes making investment decisions highly strategic (Weller et al., 2015). Despite this and the considerable research into implementation, there has been very little transfer of pre-installation principles or techniques to AM. Some implementation frameworks have been defined (Mellor et al., 2014, Achillas et al., 2014, Deradjat and Minshall, 2015), but these assume the business case has already been made and do not provide a structured pre-installation approach for evaluation or justification. With the design freedom enabled by the layering build method, literature describes part consolidation (PC) or "integrative design" as a major benefit of AM resulting in a reduction in 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., 2015, Rodrigue and Rivette, 2010). However, there is no consensus on the lifecycle impacts and very little quantification based on empirical evidence. When considering evaluation and justification, without understanding all the potential impacts of a technology and quantifying them where possible, a robust pre-installation process could never be performed. Current AM cost models, for example Ruffo et al. (2006), Baumers (2012), Baumers et al. (2016), Rickenbacher et al. (2013), and Piili et al. (2015), focus on well-structured process-related costs and do not systematically account for PC or wider lifecycle costs.

A case study research approach has been used to develop a cost model to quantify the impacts of PC on development and production costs which can be used during the pre-installation phase of AM adoption. The model has been based on a host company, where case studies were performed to identify the potential for consolidating parts within their products in terms of the number of units reduced. The host company – Malvern Instruments Ltd - design and assemble laboratory instruments for material and biophysical characterisation. The seven case studies are redesigns of existing sub-assemblies that must maintain their current internal forms, performance, and assembly with higher level assemblies, with no functional or cost optimisation. Due to the focus on the effects of PC, and to limit the scope of this study, manufacturing process cost models (build preparation to post-processing) are not constructed in this research.

Methodology

Defining the cost elements impacted by part consolidation

Existing literature outlined the potential impacts from PC on 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). However, very little empirical evidence was provided to prove them. Current AM cost models generally 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 (Thomas and Gilbert, 2014). Atzeni et al. (2010) and Atzeni and Salmi (2012) do include assembly cost based on case studies that undergo both consolidation and optimisation.

The cost model in this research was based on the *"Design and Development"* and *"Production"* stages within Lindemann et al. (2013)'s activity-based costing model based on the intrinsic product lifecycle. The elements of the cost model for each stage were defined from the perspective of PC based on activities within development and production of the host company that might be impacted by the number of parts within an assembly. Process costs defined by Lindemann et al. (2013) as "*machine preparation, material costs, machine costs, energy costs, and post-processing"* were out of scope as these are well covered within existing cost models. They also vary significantly due to machine and material costs, build speed, and post-processing requirements which would have limited the model to one type of manufacturing process.

Both well-structured and ill-structured costs were identified with respect to PC, particularly when considering the impacts on product development and the supply chain (Thomas and Gilbert, 2014, Thomas, 2015, Lindemann et al., 2012). Several cost elements (activities) originally defined were identified as being difficult to quantify in terms of time due to gaps in existing literature that would not be covered by the case studies: design review, testing, assembly review, jigs and fixtures, assembly drawings, production planning, sourcing production, external assembly operations, and quality control. Whilst reducing part count might indicate fewer design 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. Other cost elements (e.g. testing, assembly, and external sub-assembly) would require information from a top-level assembly (i.e. entire product) which was not covered by the case studies in this research which are at the sub-assembly level. The final cost elements were identified as being either one-off (development) or yearly recurring (production) costs depending on their relationship with annual production volumes. Without accounting for production volumes, the model could not accurately reflect the impact of PC on production costs. Tooling manufacture was considered within development as a one-off cost as it was an external activity for the host company and does not account for any subsequent re-tooling.

Developing the part consolidation cost model

The final cost elements were expressed in terms of a cost per unit in Table 1.

Table 1 Elements of the constructed cost model

Lifecycle stage	Cost element	Specification	Allocation base	Symbol
Development - one-off costs independent of production volume	Design and development	Development time (T_{DEV}) 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 prototype	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	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
	Kit production	Kit production time(T_{KIT}) multiplied by $\dot{C}_{LABOUR2}$		q
	Standard part manufacture	Standard part cost ($C_{STANDARD}$)	Number of standard parts ($N_{STANDARD}$)	r
	Assembly	Assembly time ($T_{ASSEMBLY}$) multiplied by $\dot{C}_{LABOUR2}$	Total number of parts (N_{TOTAL})	s

To facilitate understanding of the used approach, it is necessary to define several terms used in this research. The label *"Unit"* is used to quantify the consolidation achieved by the case studies based on the type of part relevant to each cost element. The descriptor "*Mechanical*

Item" therefore refers to the number of individually designed (bespoke) parts contained within the assembly, whilst the term "*Mechanical part"* refers to of the number of "*mechanical items*" required. As tooling is not required for AM processes, there is a need to differentiate between mechanical parts that were generated via a tooled process ("*Tooled mechanical items"* and *"parts"*) as these relied on additional activities (and therefore costs) prior to production. These are counted among *"Mechanical item"* or *"part"* for all activities that are not specifically related to tooling. The term "*Standard part"* refers to any part which is not bespoke and are generally bought out (screws, O-rings, nuts etc.). The total number of parts included all mechanical and standard parts for calculating assembly costs. Figure 2 illustrates an example breakdown of a case study according to this classification. As process costs were out of scope, the model assumed external manufacturing of prototypes, mechanical 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.

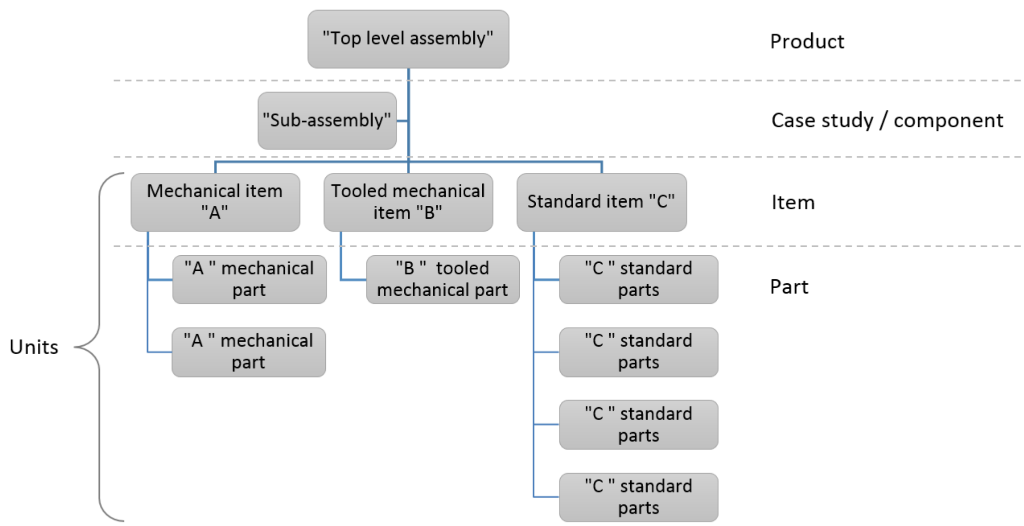


Figure 2 Classification of Units to quantify the degree of consolidation achieved by the case studies

To identify the cost impact of PC it is initially necessary to estimate the total development costs C_{DEV} and the production costs C_{PROD} using the cost elements introduced in Table 1:

$$C_{DEV} = (a + c + d + e + \big((f + g + h)N_{PROTOTYPE}\big)N_{MECHITEM} + bN_{MECHPART} + (i + j + k)N_{TOOLITEM} \quad (1)$$

$$C_{PROD} = N_{VOLUME}((l + m + n + p + q)N_{MECHPART})PL + oN_{TOOLPART} + rN_{STANDARD} + sN_{TOTAL} \quad (2)$$

Total cost for the assembly *CA* results from summing up development and production costs:

$$CA = C_{DEV} + C_{PROD} \quad (3)$$

As can be seen from equations (1) and (2), 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 potential 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 $CA_{Consolidated}$ from the total costs for the unconsolidated assembly $CA_{Unconsolidated}$:

$$IPC = CA_{Unconsolidated} - CA_{Consolidated} \tag{4}$$

Part consolidation case studies

Case studies were used to identify the potential for part consolidation within the host company and define the "*Units*" (*N*) of the cost model based on empirical evidence. The case studies were chosen to reflect a range of products covering different applications, production volumes, and functional requirements. Design methodologies for PC or functional integration resulting in a reduction in part count have been investigated, for example Rodrigue and Rivette (2010), and Yang et al. (2015). However, most specify stages for optimisation from a functional and/or cost perspective, which was out of scope to isolate PC from potential impacts from changes to functional performance. Existing research, knowledge, and expertise were used to redesign the case studies to reduce the number of parts, following Tang et al. (2016)'s assessment that AM can consolidate two or more components that need to move relative to eachother (i.e. integrated hinges and other operational mechanisms). The re-design process and methodology used is not a focus of this research. Certain types of component that could not be manufactured using AM processes were out of scope from consolidation: PCBs/PCAs, cables, wires, leads, mirrors, lens', filters, glass, and motors. Fasteners are standard parts such as O-rings, screws, dowel pins etc. were in scope but did not include those required to assemble the case studies to higher level assemblies.

Trialling the part consolidation cost model on host company

The cost and time parameters of the model were defined using data from the host company. Case studies were used to define the "*units*" for the consolidated and unconsolidated design, to indicate an achievable degree of consolidation and therefore calculate a realistic impact on costs. As mass customisation and agile development were not considered, it was assumed that each part was only developed once and then manufactured repeatedly as per demand. The same cost and time parameters were used for both designs.

Results and discussion

Identifying the potential for part consolidation within host company - the case studies

The results of the case studies in terms of the number of units for the current unconsolidated and consolidated design are summarised in Table 2. Figure 3 shows two example case studies before and after consolidation. It is noteworthy that all seven case studies resulted in a reduction of mechanical parts down to one, whilst five out of seven consolidated or eliminated all standard parts. The mechanical items and parts were consolidated by taking advantage of the design freedom enabled by AM processes – which by default meant there were no mechanical items or parts requiring tooling. This meant that organic forms could be easily created and tooling considerations such as split lines, rounds, and draft angles ignored. Consolidating the mechanical parts meant they no longer needed to be assembled and fixed together helping to eliminate most standard parts, whilst other were integrated to the AM part

(Figure 4). Case studies 2 and 3 for example required multiple screws to assemble separately machined parts, and case study 4 required screws, O-rings, and silicone sealant to make multiple separate injection moulded parts airtight. Some standard parts were integrated to the main part where they were still required for functionality: a hinge for a lid, bearings for an enclosure door, and a cable clip for routing wires (case studies 3, 5, and 7). Case studies 2 and 3 both required assembly of out of scope components (optics and a glass window) but utilised the design freedom of AM processes to integrate unique assembly interfaces. Case studies 1 and 6 however still required screws for assembling a PCB and a fibre optic cable.

Table 2 Results of the part consolidation case studies in terms of the number of units

Case study		**1**	**2**	**3**	**4**	**5**	**6**	**7**
Total number of items	Current	6	14	11	8	7	7	3
	Consolidated	2	1	1	1	1	2	1
	% reduction	*66.67%*	*92.86%*	*90.91%*	*87.50%*	*85.71%*	*71.43%*	*66.67%*
Total number of parts	Current	12	20	20	24	9	16	3
	Consolidated	5	1	1	1	1	2	1
	% reduction	*58.33%*	*95.00%*	*95.00%*	*95.83%*	*88.89%*	*87.50%*	*66.67%*
Mechanical items	Current	3	3	4	3	5	2	1
	Consolidated	1	1	1	1	1	1	1
	% reduction	*66.67%*	*66.67%*	*75.00%*	*66.67%*	*80.00%*	*50.00%*	*0.00%*
Mechanical parts	Current	3	4	4	6	5	2	1
	Consolidated	1	1	1	1	1	1	1
	% reduction	*66.67%*	*75.00%*	*75.00%*	*83.33%*	*80.00%*	*50.00%*	*0.00%*
Tooled mechanical items	Current	2	0	0	2	0	0	1
	Consolidated	0	0	0	0	0	0	0
	% reduction	*100.00%*	*n/a*	*n/a*	*100.00%*	*n/a*	*n/a*	*100.00%*
Tooled mechanical parts	Current	2	0	0	4	0	0	1
	Consolidated	0	0	0	0	0	0	0
	% reduction	*100.00%*	*n/a*	*n/a*	*100.00%*	*n/a*	*n/a*	*100.00%*
Standard parts	Current	9	16	16	18	4	14	2
	Consolidated	4	0	0	0	0	1	0
	% reduction	*55.56%*	*100.00%*	*100.00%*	*100.00%*	*100.00%*	*92.86%*	*100.00%*

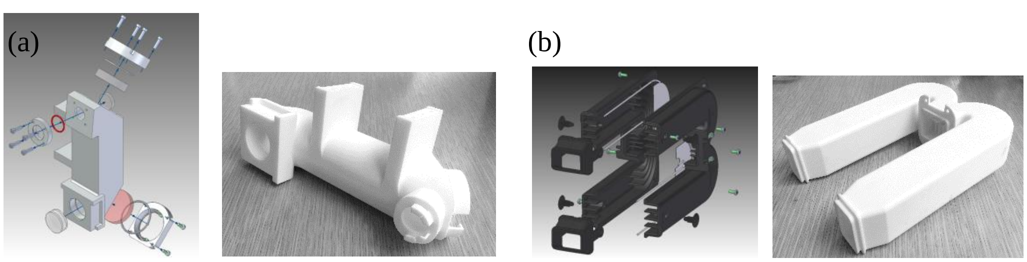


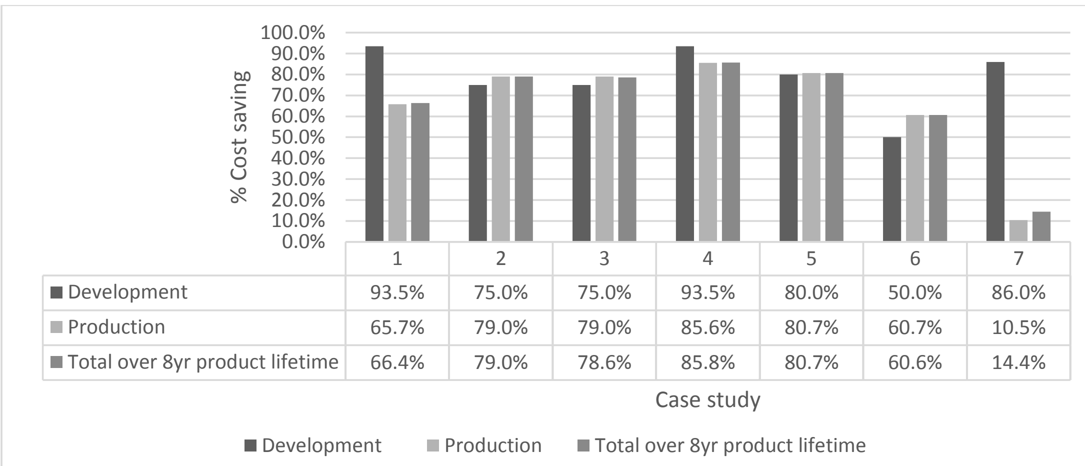
Figure 3 Case study 3 (a) and 4 (b) showing the before and after consolidation

Standard parts	
Eliminated	**Integrated**
Screws, glue, silicone sealant, inserts, magnet, springs, tree clips, O-rings, nuts, washers, dowel pin, grease, rivets	Hinge, bearings, cable clip

Figure 4 Standard parts eliminated or integrated through PC using AM

Impact of PC on costs for host company

Figure 5 shows the results of the case studies in terms of a percentage cost saving achieved by the consolidated assembly for development, production, and total costs *(C_{PC})* assuming an 8yr production life. All case studies achieved a development cost saving of between 50% and 93.5%. Case study 7 however achieved only a 10.5% production cost saving compared to between 60.7% and 85.6%, resulting in a total cost saving of only 14.4% compared to between 60.6% and 85.8%. This indicates that production costs were a bigger proportion of total costs than development. To verify, Table 3 summarises the cost saving for each cost element across all the case studies, as well as the contribution of those costs to development and production costs, and total costs. It shows that production costs accounted for significantly more than development, at 97.77% of the total cost saving. This result differ from Lindemann et al. (2013) who found that the design and development phase was the biggest contributor to total costs. However, their model was not formulated to capture the effect of PC.



	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 5 Bar chart showing the cost saving achieved through part consolidation for each case study for development, production, and total costs assuming an 8yr production life

Within Production costs, *Mechanical part manufacture* was the biggest contributor to the total cost saving at 66.23%. The next most significant contributor was the cost of *Standard part manufacture* (11.81%), followed by *Order production* parts (8.10%) and then *Assembly* (6.97%). This reflects the results of Atzeni et al. (2010) who calculated that assembly had a smaller impact on costs than the manufacturing process, though this was based on a relatively simple 3-part assembly case study. When considering AM costs, it is well understood that these can vary significantly depending on the machine and material costs, machine productivity, and post-processing requirements (Baumers et al., 2016). This would imply that the chosen AM process for production of the consolidated assemblies would have an impact on potential cost savings from PC. As specified by AM design methodologies and research however (Yang et al., 2015, Rodrigue and Rivette, 2010), designs should be optimised from a functional and cost perspective to improve performance and reduce build time and post-processing requirements. None of the case studies in this research have undergone any optimisation so would not give a realistic indication of manufacturing costs. This can be justified on the basis that AM costs must be considered on a case by case basis. More work should be done to understand whether the lifecycle cost implications from PC outweigh increases in manufacturing process costs.

Table 3 Total cost reduction and proportion of costs for each cost element

Cost element	***Cost reduction across all case studies***	***Proportion of impact on lifecycle stage***	***Proportion of impact on 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 prototype	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) Tool sourcing discussion	100%	0.29%	0.01%
(j) Tooling design & analysis	100%	11.92%	0.27%
(k) Tooling manufacture	100%	54.92%	1.23%
TOTAL Development	**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%
TOTAL Production	**72.43%**	**100%**	**97.77%**
TOTAL Product lifecycle (8yrs)	**72.70%**	**n/a**	**100%**

The next step in the analysis is to investigate which type of part (mechanical, tooled mechanical, or standard) had the biggest impact on costs through consolidation. Figure 6 shows a simplified linear model of the degree of consolidation against production cost saving for all the case studies for each type of part. It is clear from these results that higher cost savings can be achieved when consolidating significant numbers of mechanical parts. Case study 7 does not achieve significant cost savings because it had very limited consolidation potential with only one mechanical item. However, both standard parts were eliminated or consolidated, and no tooling was required. This indicates that even with no consolidation of mechanical parts, cost savings can still be achieved by eliminating tooling related costs and integrating or eliminating standard parts such as cable clips and screws.

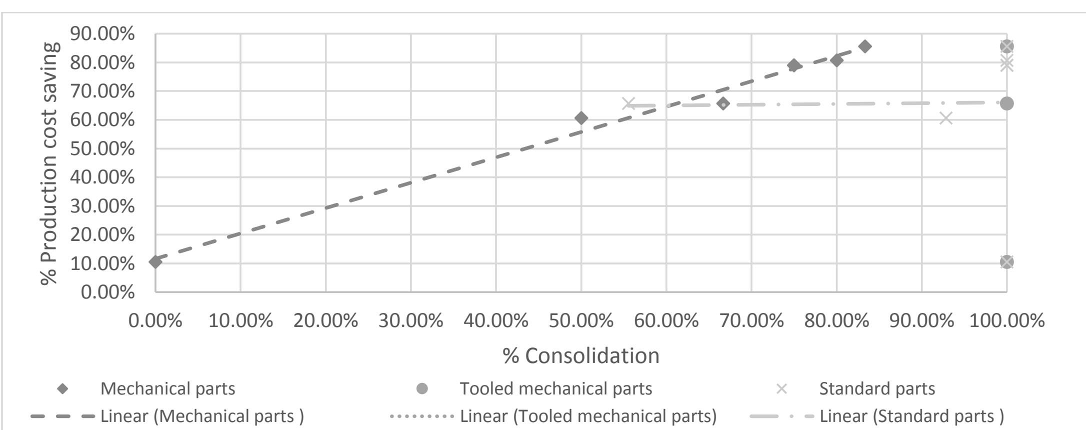


Figure 6 Consolidation against production cost saving for the mechanical parts, tooled mechanical parts, and standard parts

Other tangible and intangible benefits of PC outside of development and production have not been properly considered within this research. For example, reducing tolerance accumulation and the impacts on functionality and quality control; increasing robustness to reduce servicing and repair costs; simplifying service and end of manufacture supply chains; improving disassembly and recycling at end of life; and reducing environmental impacts. Reducing the number of parts and development time could result in reduced time to market and increased sales; whilst lower product downtime with improved functionality and reduced lead times could increase customer satisfaction. The model does also not reflect the cost of redesigning the case studies, or the costs required for the implementation process. Some AM implementation frameworks have been developed which could be used to help identify other implementation-related costs (Mellor, 2014, Deradjat and Minshall, 2015, Achillas et al., 2014, Oettmeier and Hofmann, 2016). Existing AM cost models could also be developed to account for the potential increase in costs from increased complexity of the consolidated design, for example on removing powder from internal cavities for laser sintered components.

Conclusion

A cost model has been developed to quantify the impacts of PC on development and production costs. This analysis yields a simplified linear model of cost savings resulting from reducing part count which can be used to predict potential cost savings resulting from PC. It shows that the more significant the consolidation, the higher the potential cost savings. The model trial is based purely on costs of the host company, meaning the results could vary for other companies in terms of the total cost impact and the proportion of impact from each cost element. Though parallels could be drawn from the host company in this research to an adopting organisation, this model is proposed as a tool to be used during the pre-instillation phase of implementation. It should therefore be adapted to reflect the business model, costs, and potential for PC based on case studies from the adopting organisation. The case studies in this research showcase the potential design freedom from AM processes for manufacturing complex forms, but are limited by maintaining original functionality with no optimisation. The model also does not reflect full lifecycle or intangible benefits of PC, and other benefits from mass customisation and functional optimisation should also be considered when justifying AM adoption.

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