Control Architectures for Industrial Additive Manufacturing Systems

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Abstract *Industrial Additive Manufacturing technologies are increasingly being employed in manufacturing environments, yet there has been little consideration of these in terms of manufacturing systems. This paper explores the important concept of control for Industrial Additive Manufacturing Systems, drawing upon data achieved in twelve case studies to identify four feasible control architectures. Using an abductive approach, this paper contributes to a recognized knowledge gap in operations and manufacturing management research.*

1. Introduction

Industrial Additive Manufacturing technologies such as Laser Sintering, Stereolithography, and Fused Deposition Modelling are increasingly being employed in the production of end-user products, rather than traditional prototyping applications (Wohlers 2014). For some applications (e.g. art, lighting, aerospace, and military products) the use of Industrial Additive Manufacturing technologies constitutes an emergent production technique, however for customized products such as medical implants, dental parts, hearing aids, and jewellery these technologies have already started to replace conventional techniques, offering enhancements on many attributes such as responsiveness and quality (Eyers and Dotchev 2010). These improvements in operational characteristics, combined with greater commercial awareness of the potential for the technologies has resulted in increased adoption of Additive Manufacturing by a range of manufacturers and service bureaus.

This progression from prototyping to manufacturing has not been accompanied with commensurate research in terms of implications for operations and manufacturing management. Most recently Bianchi and Åhlström (2014) have emphasized a prevalence for fundamental engineering/science research, rather than operations management research; an observation supported by Taylor et al. (2013) who have highlighted that technological developments are “out pacing” the development of complementary business knowledge. Such disjunction between technical and management research is problematic in the application of technologies, since it is well established as impairing the achievement of competitive advantage (Hyun and Ahn 1992). The purpose of the current study is to provide some redress for this identified research gap by examining the nature of control for Industrial Additive Manufacturing Systems, with particular emphasis on the control architectures that are evidenced in commercial practice. The study builds on prior work that has explored the nature of Industrial Additive Manufacturing Systems (Eyers and Potter 2015), and by focusing on system control from a management perspective, provides a timely contribution to academic and practitioner knowledge.

The paper commences with a literature review that identifies the nature of control within manufacturing systems, and evaluates the limited extant research in the context of Industrial Additive Manufacturing. Using an abductive approach in which theoretical propositions are explored in conjunction with empirical data, four control architectures are subsequently defined and evaluated for Industrial Additive Manufacturing Systems. Conclusions are provided, and an agenda for further research is developed in the closing of this paper.

2. Literature Review

2.1 Control in Manufacturing Systems

The effective operation of a manufacturing system requires that, despite the external influences placed upon it, long-term stable operation is achieved through having appropriate control systems in place (Parnaby and Towill 2009). The importance of control within the manufacturing system is paramount, as Baker (1998, p. 300) observed "factory control is the central nervous system of a factory; it co-ordinates the use of the factory's resources, giving the system its purpose and meaning". Ideally, control systems should be designed with such flexibility that they are able to adapt to accommodate disturbances, however in practice this is not always the case (Brennan 2000).

In his definition of a manufacturing system, Parnaby (1979) identified control as being multi-level, and hierarchical in nature. This is supported by He et al. (2014), who have claimed that manufacturing systems are always hierarchical, and advocate the control system should therefore follow this structure as much as possible. The focus of control in both theory and practice can often be seen to follow such an alignment, with attention to control frequently considered at machine, cell, and factory / whole system levels.

This hierarchical approach to the control of the internal production system is consistent with many of the early approaches to the control of manufacturing systems (e.g. O'Grady 1986). However Brennan and O (2004) identify that the functional activities undertaken in manufacturing control should be distinct from the architecture of the control system, allowing activities to be undertaken by entities within the system, interconnected within the control architecture (Figure 1).

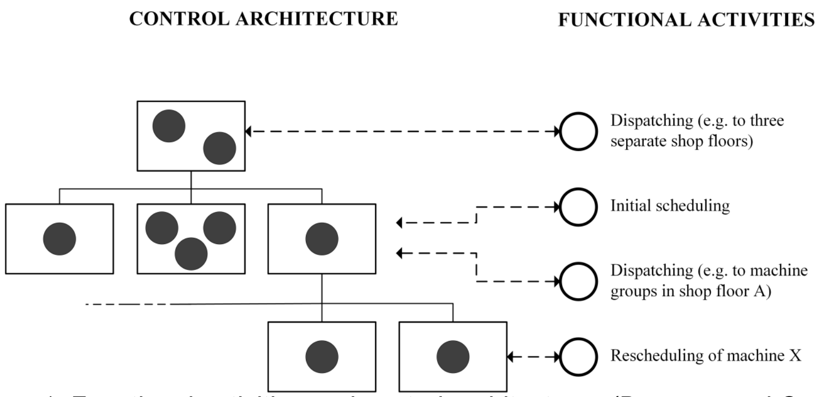


Figure 1: Functional activities and control architectures (Brennan and O, 2004)

Dilts et al. (1991) identified that different control architectures define the way in which process components interact, and affect the flow of monitoring and control information within the system. At the most fundamental level, control architectures allocate decision making responsibilities to control components; by changing the architecture the way in which the system is controlled may be substantially altered. Four different control architectures have been proposed by Dilts et al. (1991) in the context of automated manufacturing, which despite being almost a quarter of a century old, still remain a popular means of characterizing control architectures for generic applications in contemporary works (e.g. Haneyah et al. 2013):

Centralized Form was the first form of manufacturing control system, in which a single control component makes decisions for all of the manufacturing entities of the system. In this approach, decision-making control occurs at a single location, with distributed non-intelligent controllers executing these decisions at a local level. As with the hierarchical forms described subsequently, the centralized form mirrors the physical hierarchy of a manufacturing system, but lacks operational flexibility as a result of the centralized control (Columbo et al. 2006; He et al. 2014).

Proper Hierarchical Form decomposes the manufacturing system into a number of different levels, for which each sub-layer is a slave to the master above it. In this form, control decisions occur top-down, with the aggregate decisions occurring at the uppermost levels and more detailed decisions made at lower levels (Jones and McLean 1986). Conversely, the system status is reported bottom-up to the uppermost levels. Effectively, such hierarchical approaches operate similarly to centralized architectures, with managerial activities such as scheduling occurring at higher levels, and execution at lower levels (Duffie and Prabhu 1994).

Modified Hierarchical Form is an extension on the Proper Hierarchical Form that allows communication in a peer-to-peer relationship between control system entities. In this form, greater autonomy is granted to the individual manufacturing entities, and greater processing and decision making performed by these than in the previous two forms (Dilts et al. 1991). This localization of control improves the robustness of the system to random disturbances, and its ability to respond quickly to changing conditions. However, vertical control and horizontal communication between entities requires management, which can be a challenge for hierarchical-based approaches (Morel et al. 2007).

Heterarchical Form arose in the 1980's as an alternative to the hierarchical approach to control. Heterarchical control architectures enable local autonomy for manufacturing entities, and removes the master/slave relationship found in the hierarchical architectures (Duffie and Piper 1986). The manufacturing control system is effectively distributed amongst a network of intelligent agent controllers, each managing their local resource. Importantly, the physical system configuration is transparent to the entities of the system: there is no need for these to know where other entities reside (Duffie and Prabhu 1994). Within a co-operative heterarchy, Duffie and Prabhu (1994, p. 95) identify:

1. Entities have equal rights of access to resources.
2. Entities have equal mutual access and accessibility to each other.
3. Entities have independent modes of operation.
4. Entities strictly conform to the protocol rules of the overall system.

Although heterarchical control systems promote fault tolerance and localized optimization, it is identified that this may be at the detriment of an overall global optimization for the manufacturing system (He et al. 2014).

In addition to these four architectures, it is acknowledged that alternate approaches are also promoted for manufacturing systems. Increasing requirements for flexibility, robustness, responsiveness, and configurability are challenging the suitability of the traditional centralized and hierarchical control architectures (Leitão 2009), leading to other approaches being implemented including holonic and agent-based control architectures.

2.2 Control in Industrial Additive Manufacturing Systems

Consideration of control within Parnaby's (1979) manufacturing system requires that attention is given to all system resources, not just individual machines. There is, however, a dearth of knowledge considering Additive Manufacturing from a systems perspective (Eyers and Potter 2015), and of the very few studies that consider control, the emphasis is on technical implementation of control for individual machines, with no attention given to overarching control architectures.

The established literature suggests that in implementation, Additive Manufacturing systems may be delimited as having either centralized or decentralized approaches. In centralized architectures Nagel and Liou (2010) focused on control from the perspective of electrical or mechanical control, including PLC's, OEM integrated systems, and DIY systems produced by the manufacturer. These are principally machine-focused approaches to control, without integration with other components of the manufacturing system. For example, in related work for 3D printers, Hoske (2013) notes that a lack of feedback from the machine processes inhibits closed-loop control. Similarly, Espalin et al. (2014) highlighted the use of reconfigurable real-time controllers to operate the system, and the role for both hardware and software to support control objectives using finite state machines.

For decentralized architectures (typically defined in the Additive literature as 'web-based'), consideration of system control has centered on Internet-based 'tele-control' (Luo et al. 1999; Luo et al. 2001) in which the control of the physical manufacturing processes is achieved remote to the physical machines. For these approaches control remains at a machine level, but with increased emphasis on the mechanisms by which information systems are coordinated to support remote control of machines.

Whilst these studies provide useful insights relevant to the current paper, it is evident that there is a lack of work concerning system control and supporting architectures. Such observations provide justification for this study, highlighting the emergent nature of the concept and the need for exploratory work to better understand the opportunities for Industrial Additive Manufacturing Systems.

3. Research Method

This study is part of a larger investigation, and supports other work by the author (Eyers and Potter 2015) that has focused on Industrial Additive Manufacturing from the systems perspective promoted by (Parnaby 1979) and Parnaby and Towill (2009). Through this work it has been shown that four principal system components (design, pre-processing, manufacturing, post-processing) arise through 36 distinct activities in Industrial Additive Manufacturing Systems. A range of enabling mechanisms are employed in the achievement of manufacturing including machine resources (of varying degrees of automation), labour resources (of varying skill capabilities), and information processing resources (of varying natures), each of which requires control.

An abductive approach was taken in this study, through which empirical observation is matched with theory, and from which new theory can be developed (Kovács and Spens 2005). In this work, data from twelve case studies (Table 1) were explored in the context of the existing control architecture theory (explored in section 2.2). Data for this study was gained through interviews and process observation at three manufacturers employing Industrial Additive Manufacturing, supported by additional data provided by these companies and semi-structured interviews with customers. This use of qualitative methods is consistent with this type of exploratory research, where theories are suggested through open-ended enquiry (Edmondson and McManus 2007).

Case	Mfr	Product Description	Technology
1	A	In-The-Ear (ITE) hearing aid	DLP
2	B	Archaeological reconstruction of model ship	LS
3	B	Archaeological reconstruction of medieval stones	LS
4	B	Model building (student architecture project)	LS
5	B	Hydroform tool for exhaust system	SLS
6	B	Inspection fixture for toothbrush product	SLS
7	B	Functional prototype of exhaust sensor tool	LS
8	C	Guide for surgical applications	LS
9	C	Customized lighting product	LS
10	C	Standardized lighting product	LS/SL
11	C	Hybrid fixture system (customized)	LS
12	C	Designer furniture product	LS

Table 1: Summary of case studies explored in this research

4. Findings

The qualitative investigation explored the operations of the three manufacturers, and identified that selection of control architectures was company, rather than product specific. Although the cases show a wide range of different products, technologies, and applications/customers, in practice control architectures were shown to align to the organizational structures of the companies. Most notable was a reliance on human intervention to achieve control, with only limited application of computer technology. Whilst emphasis in the literature has long prescribed the application of computers in the production and control process (without which control would be “inconceivable” (Kochhar et al. 1995, p. 411)), within the focal systems only rudimentary use of computers for such activities was identifiable.

In Table 2, a summary of the identified control architectures is presented, using three criteria originally prescribed by Dilts et al. (1991) to highlight the implication of these for operations:

- Reconfigurability is the ability to change the control of the manufacturing system, in response to characteristics such as machine failure or unexpected requirements placed on the system.
- Extensibility is the ability for existing elements of the system to be modified, for example in the extension to include new components.
- Fault tolerance is the ability of the system (and its architecture) to accommodate faults without failure, and therefore to achieve continued reliability

A fourth criteria, autonomy is introduced to reflect the ability of the control elements of a manufacturing system to operate with autonomy of other elements within the system.

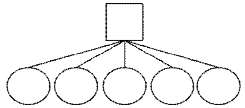
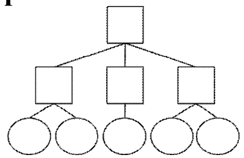
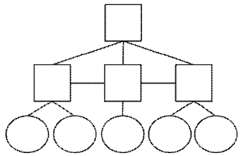
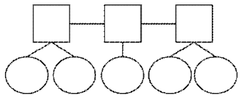
Mfr & Case(s)	Control Architecture	Reconfigurability	Extensibility	Fault Tolerance	Mfg Autonomy
B 2 - 7	**Centralized Form** 	Low	Low	Low	Low
A 1	**Proper Hierarchical Form** 	High	Medium	Medium	Medium
C 8-12	**Modified Hierarchical Form** 	High	Medium	Medium	Medium
C Collaborative	**Heterarchical Form** 	High	High	High	High
Control component Manufacturing entity Control interrelationship					

Table 2: Identified control architectures for Industrial Additive Manufacturing Systems

Centralized Form: Mfr B

Mfr B is a small Additive Manufacturing bureau, with a range of different machines and three permanent staff to perform all activities associated with manufacturing. A single manufacturing facility exists, with labour and infrastructure resources shared between each of the different manufacturing process types. Within this system, planning and co-ordination of all operations is performed centrally by the commercial manager, representing a central control element in the system. Such a configuration is typical in small Additive Manufacturing bureaus, wherein a few machine resources are controlled by a single control entity.

At the cell level decision making is minimal, and is largely based on the established procedures implemented by the central controller. Examples of cell-level decision making typically focused on approaches to achieve effective finishing of parts. Manufacturing autonomy is therefore low. Parts are produced according to the instructions of the controller, and established relationships between the controller and manufacturing entities are tight and long-term. As there is no electronic feedback mechanism, feedback arises from the human operators rather than through the Additive Manufacturing process resources, and is therefore manual, ad-hoc, and typically informal in nature. This leads to identified difficulties in planning and scheduling of work, and as a result the controller does not plan for full utilization of the system's resources.

The system comprises of individual instances of Industrial Additive Manufacturing machines, with no redundancy in the event of component failure. Similarly, there is little opportunity to interchange resources. The system has no defined options for expandability or reconfiguration, and does not collaborate with any other manufacturer. This has negative implications for the company which were demonstrated during this research when an extended period of machine downtime was observed for one of the manufacturing processes. During this time *Mfr B* was unable to satisfy customer orders, and as a result some orders were delayed and some orders lost to other companies. Similarly, during this research the amount of work for the system decreased significantly, yet there was no reconfiguration of system control in reflection of this change.

Proper Hierarchical Form: Mfr A

As a member of a larger group of companies, the manufacturing operations of *Mfr A* operate relatively autonomously from other group companies, but within the overall control of a central control entity. As a result, from a single UK manufacturing site the company fulfils demand for UK and Western Europe, with a dedicated production line producing customized ITE Hearing Aids. A management hierarchy oversees the facility, with dedicated production planners managing the planning and co-ordination of all operations. Control is therefore delegated hierarchically through the operations, with individual elements of the operations under control of local controllers.

Large variability in order volumes on a daily basis requires reconfiguration of labour within the manufacturing system to optimize its usage. Multi-skilled staff move between order processing, design, manufacturing, and assembly activities as required to maximize their utilization. This is controlled centrally by the production

manager, and can also be reliant on individual team-leaders in execution. A clearly defined production process, together with a factory layout promoting series-based production means that work moves between workstations independent of the controller; however there is very little feedback of in-process activity. Unless a manual request for feedback is instigated, controllers have little awareness of the state of a given entity of the manufacturing system.
The system comprises of multiple instances of machine and labour resources that can be interchanged in the event of component failure, however there is no excess capacity for redundancy. In the event of a major failure of the system the ability exists to reallocate work to a different system within the network, however this is neither seamless nor desirable. In the event of this occurrence, manufacturing control is delegated to the alternate system.
It is identified that expansion of the system may be achieved using additional components; however the ability of the central controller to manage increasing numbers of manufacturing entities constrains the extent of such extension. During the conduct of this research there was no demonstration of this capability.

Modified Hierarchical Form: Mfr C
Mfr C splits its manufacturing systems into specialist facilities (for medical device production), and generalist facilities for all other production requirements. It employs two sites for its most specialized medical applications, in Europe and in the US. This second US based site provides additional production capacity for specialised medical components, local to demand for US customers. Each manufacturing system has assigned resources that are specialized, and therefore these are not typically shared between systems. Overall control of the multiple systems occurs at the European headquarters.

Each system is under the responsibility of a single director, and is distinctly controlled by production planners who schedule work using the company's planning software. Control is therefore delegated hierarchically through the operations, with individual elements under control of local controllers. An individual system comprises of multiple instances of machine and labour resources that can be interchanged in the event of component failure, however there is no excess capacity for redundancy. Compared to the Proper Hierarchical form, the principal difference observed in this example is the inter-relationship between manufacturing systems. Work and resources can often be switched within manufacturing systems without major penalty, and this is frequently employed to achieve load-balancing across the entire company's demand. Notably this is constrained by some of the specialist applications requiring particularly high quality production (e.g. medical parts), where dedicated systems are essential in promoting both quality and repeatability.

Heterarchical Form: Mfr C Joint Venture
True heterarchical form requires that a manufacturing system has no overall supervisor, with entities self-configuring in the achievement of manufacturing. It is noted that in the context of Additive Manufacturing a similar notion was proposed

by Berlak and Webber (2004) in ‘competence networks’, however in this system a definite controller coordinates the product fulfilment process.

Within the current study it is identified that several companies in the Additive Manufacturing industry have joined together in a heterarchical-like form, and *Mfr C* is a participant member. As demand is placed upon the system, individual companies take work based on their competencies, capacity, and potential responsiveness (the latter often dictated by production location relative to demand). Each manufacturer controls its own production, and therefore has a high degree of autonomy in manufacturing. Similarly, there exists some redundancy in the system, since the system is able to draw upon the capabilities of a distributed network of major manufacturers. Communication within the system is identified as good, with most information shared using the internet. The focal heterarchical system is a closed system; members are fixed and so unlike a marketplace there is little movement in-and-out of the system. Nevertheless, relative to the other control architectures, relationships within the system are loose and transient.

5. Conclusion

Control architectures directly affect the flow of control and monitoring information, and the interaction of the manufacturing process components (Dilts et al. 1991), and are therefore important for management of any manufacturing system. This paper has examined the concept of control architectures for Industrial Additive Manufacturing Systems, highlighting the lack of research consideration that has been afforded to this important topic. Through an abductive approach this paper has demonstrated four different control architectures for Additive Manufacturing, providing a discussion of the characteristics of individual implementations.

This exploratory study provides an initial investigation into the concept of control architectures for Industrial Additive Manufacturing Systems, however it is acknowledged that further work is needed to extend and develop this knowledge further. Three most pertinent directions for further work are:

1. Exploration of the implications on flexibility arising from the selection of different control architectures, in order to identify opportunities to maintain/enhance flexibility in the system.
2. Examination of developments in holonic and agent-based control for Industrial Additive Manufacturing Systems that are outside the scope of this exploratory work.
3. Extension of the current study to a wider range of manufacturing companies, particularly to identify multiple cases employing each of the control architectures.

6. References

Baker, A. D. 1998. A survey of factory control algorithms that can be implemented in a multi-agent heterarchy: Dispatching, scheduling, and pull. *Journal of Manufacturing Systems* 17(4), pp. 297-320.

Berlak, J. and Webber, V. 2004. How to configure cyber chains via competence networks. *Business Process Management Journal* 10(3), pp. 291-299.

Bianchi, M. and Åhlström, P. 2014. Additive manufacturing: towards a new operations management paradigm? In: *20th International EurOMA Conference.* Palermo, Italy, 20-25 June 2014.

Brennan, R. W. 2000. Performance comparison and analysis of reactive and planning-based control architectures for manufacturing. *Robotics and Computer-Integrated Manufacturing* 16(2-3), pp. 191-200.

Brennan, R. W. and O, W. 2004. Performance analysis of a multi-agent scheduling and control system under manufacturing disturbances. *Production Planning & Control* 15(2), pp. 225-235.

Columbo, A. W., Schoop, R. and Neubert, R. 2006. An agent-based intelligent control platform for industrial holonic manufacturing systems. *IEEE Transactions on Industrial Electronics* 53(1), pp. 322-337.

Dilts, D. M., Boyd, N. P. and Whorms, H. H. 1991. The evolution of control architectures for automated manufacturing systems. *Journal of Manufacturing Systems* 10(1), pp. 79-93.

Duffie, N. A. and Piper, R. S. 1986. Nonhierarchical control of manufacturing systems. *Journal of Manufacturing Systems* 5(2), pp. 137-139.

Duffie, N. A. and Prabhu, V. V. 1994. Real-time distributed scheduling of heterarchical manufacturing systems. *Journal of Manufacturing Systems* 13(2), pp. 94-107.

Edmondson, A. C. and McManus, S. E. 2007. Methodological fit in management research. *Academy of Management Review* 32(4), pp. 1155-1179.

Espalin, D., Ramirez, J. A., Medina, F. and Wicker, R. 2014. Multi-material, multi-technology FDM: exploring build process variations. *Rapid Prototyping Journal* 20(3), pp. 236-244.

Eyers, D. R. and Dotchev, K. D. 2010. Technology review for mass customisation using rapid manufacturing. *Assembly Automation* 30(1), pp. 39-46.

Eyers, D. R. and Potter, A. T. 2015. The concept of an Industrial Additive Manufacturing System. In: *26th Annual POMS conference.* Washington D.C., 8-11 May 2015.

Haneyah, S. W. A., Schutten, J. M. J., Schuur, P. C. and Zijm, W. H. M. 2013. Generic planning and control of automated material handling systems: Practical requirements versus existing theory. *Computers in Industry* 64(3), pp. 177-190.

He, N., Zhang, D. Z. and Li, Q. 2014. Agent-based hierarchical production planning and scheduling in make-to-order manufacturing system. *International Journal of Production Economics* 149(0), pp. 117-130.

Hoske, M. T. 2013. Additive manufacturing: Disruption or evolution? *Control Engineering*.

Hyun, J.-H. and Ahn, B.-H. 1992. A unifying framework for manufacturing flexibility. *Manufacturing Review* 5(4), pp. 251-260.
Jones, A. T. and McLean, C. R. 1986. A proposed hierarchical control model for automated manufacturing systems. *Journal of Manufacturing Systems* 5(1), pp. 15-25.
Kochhar, A. K., Oldham, K. and Thacker, S. M. 1995. Structured methodology for the selection and effective implementation of manufacturing control systems. *Science, Measurement and Technology, IEE Proceedings* 142(5), pp. 411-416.
Kovács, G. and Spens, K. M. 2005. Abductive reasoning in logistics research. *International Journal of Operations & Production Management* 35(2), pp. 132-144.
Leitão, P. 2009. Agent-based distributed manufacturing control: A state-of-the-art survey. *Engineering Applications of Artificial Intelligence* 22(7), pp. 979-991.
Luo, R. C., Lee, W. Z., Chou, J. H. and Leong, H. T. 1999. Tele-control of Rapid Prototyping Machine via internet for automated tele-manufacturing. In: *IEEE International Conference on Robotics and Automation.* pp. 2203-2208.
Luo, R. C., Tzou, J. H. and Chang, Y. C. 2001. Desktop rapid prototyping systems with supervisory control and monitoring through Internet. *IEEE/ASME Transactions on Mechatronics* 6(4), pp. 399-409.
Morel, G., Valckenaers, P., Faure, J.-M., Pereira, C. E. and Diedrich, C. 2007. Manufacturing plant control challenges and issues. *Control Engineering Practice* 15(11), pp. 1321-1331.
Nagel, J. K. S. and Liou, F. W. 2010. Designing a modular Rapid Manufacturing process. *Journal of Manufacturing Science and Engineering-Transactions of the ASME* 132(6).
O'Grady, P. J. 1986. *Controlling automated manufacturing systems*. London: Kogan Page.
Parnaby, J. 1979. Concept of a manufacturing system. *International Journal of Production Research* 17(2), pp. 123-135.
Parnaby, J. and Towill, D. R. 2009. Exploiting the concept of a manufacturing system. Part I: The relationship with process control. *Journal of Manufacturing Technology Management* 20(7), pp. 915-932.
Taylor, M., Taylor, A., Walters, D. and Bhattacharjya, J. 2013. Additive manufacturing: a route to recovery? In: *20th International EurOMA Conference.* Dublin, Ireland, 9-11 June 2013.
Wohlers, T. T. 2014. *Wohlers Report 2014*. Fort Collins, Colorado: Wohlers Associates Inc.