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Control architectures for Industrial Additive Manufacturing Systems

Daniel Eyers

Abstract

As the emergent technologies of Industrial Additive Manufacturing become increasingly employed in commercial manufacturing environments, challenges arise in terms of how resources of the manufacturing system should be marshalled and controlled for sustainable manufacturing. Whilst control architectures are well-established for conventional manufacturing, to-date there has been little explicit consideration for Industrial Additive Manufacturing. This paper provides redress for this research gap by exploring four feasible control architectures employed in current manufacturing practice. Drawing upon twelve case studies and the operations of three companies, the relative merits, demerits, and challenges for each architecture is explored in terms of changeability criteria for sustainable manufacturing.

Introduction

Despite decades of research, the integration of emergent technologies within manufacturing environments remains a major challenge for academics and practitioners alike. Emergent technologies are characterised by their novelty, relatively fast growth, coherence, prominent impact, and uncertainty/ambiguity¹, and these attributes require careful management to afford an optimal and sustainable implementation. One such emergent technology is that of 'Additive Manufacturing'²⁻⁴, which is a process that builds physical parts from 3D model data through the incremental addition of layers of material. There are many different processes characterised by the Additive Manufacturing terminology, and these are frequently delimited into two categories based on cost: machines costing less than \$5,000 are termed 'personal', whereas more expensive machines (tens or hundreds of thousands of dollars) are classed as 'industrial'⁵. Personal machines tend to be used by individual hobbyists and educational users⁶, whereas industrial

machines offer professional capabilities that are often implemented within whole manufacturing systems, comprising a range of machine, labour, and information processing elements⁷.

The subset of Industrial Additive Manufacturing technologies explored in this study raise interesting challenges for control and sustainability that have to-date received little research attention. Unlike personal machines (where control focuses on the fundamental control of machine processes), industrial systems implementations require effective control between a multitude of process components to achieve manufacturing that is both sustainable and competitive. For these Industrial Additive Manufacturing Systems the commercial objective is to effectively exploit the well-documented advantages demonstrated in prototyping and laboratories, but within the constraints of competitive real-world sustainable manufacturing.

This progression from prototyping to manufacturing has already started for Industrial Additive Manufacturing technologies such as Laser Sintering (LS), Stereolithography (SL), and Fused Deposition Modelling (FDM), and there is much future potential for several metal powder bed fusion processes. Whilst the ability to viably produce one-off parts and prototypes has remained an important characteristic of the technologies⁸, increasingly higher volume production has been evidenced in recent years, particularly for applications where Additive Manufacturing has displaced other techniques such as medical implants and hearing aids⁹. Although many challenges remain concerning the industrial application of Additive Manufacturing¹⁰, ongoing improvements in operational characteristics, combined with greater commercial awareness has resulted in increased adoption of Additive Manufacturing by manufacturers and service bureaus alike¹¹.

As the additive technologies are increasingly used in manufacturing environments, the importance of control to ensure competitive and sustainable production becomes paramount. In *prototyping*, the focus is typically on the production of single parts by individual machines for which control is comparatively simple and resources easily managed. By comparison, in *manufacturing*, a plethora of different parts and production volumes may be required, involving a wide range of resources, all of which need to be effectively controlled to optimize utilization and minimize waste.

Control is fundamental to the effective management of manufacturing systems¹²⁻¹⁴, and this study focuses on control architectures from a sustainable manufacturing perspective. Without effective control manufacturing is chaotic, and so whilst Additive Manufacturing technologies may have technical characteristics that can ‘revolutionize’ manufacturing^{15, 16}, appropriate control is an essential requirement for the ongoing achievement of sustainable manufacturing, yet very little research has addressed this.

The principal contribution of this study is the extension of the control concept for Industrial Additive Manufacturing Systems, allowing the critique of control architectures as evidenced in commercial practice. The paper commences with a literature review that identifies the nature of control within manufacturing systems, and evaluates the limited available research in the context of Additive Manufacturing and sustainability. 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, and detailed discussion of the implications for sustainable manufacturing given.

Literature Review

Control in Manufacturing Systems

Manufacturing systems transform raw materials into products, gaining a higher value in the process¹². Manufacturing systems consist of multiple distinguishable related units (e.g. machines, labour etc.), which through their operation and environmental adaption seek one or more goals¹⁷. In an ideal world these resources would enjoy a steady operation, but in practice disruptions arise externally (e.g. demand variation, negative competitor activities) and internally (e.g. equipment breakdown, labour absenteeism). As a result, to achieve a long-term stable operation of the manufacturing system in spite of internal and external disturbance it is necessary to have appropriate control systems in place^{14, 18}. The achievement of this control is often difficult, since manufacturing systems are both dynamic and complex, with individual processes, subsystems, and inter-system interactions all requiring integration and control. Nevertheless, the importance of control within the manufacturing system is paramount, as Baker¹⁹ 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 case²⁰.

Multiple approaches have been taken to the control of manufacturing systems. In his definition of a manufacturing system, Parnaby¹² identified control as being multi-level, and hierarchical in nature. This is supported by He and Zhang²¹, 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 perspective on the control of the production system is consistent with many of the early approaches to the control of manufacturing systems (e.g. O'Grady²²). However Brennan and O'²³ 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).

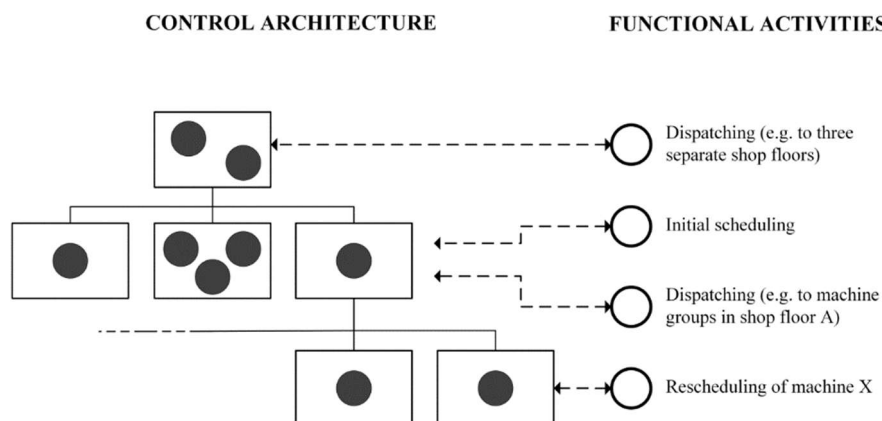


Figure 1: Functional activities and control architectures (Brennan and O, 2004)

Dilts et al.²⁴ 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.²⁴ 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.²⁵, Jovanović et al.²⁶). These architectures are discussed in the following sections, supported by an overview in Table 1.

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^{21,27}.

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 levels²⁸. 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 levels²⁹.

Modified Hierarchical Form is an extension of 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 forms²⁴. 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 approaches³⁰.

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 architectures³¹. 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 reside²⁹. Within a co-operative heterarchy, Duffie and Prabhu²⁹ 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 system²¹. As a result, whilst there has been much enthusiasm for such approaches, great care needs to be taken to ensure alignment between local and global decision making.

Control Architecture	Advantages	Disadvantages
Centralized	Global access to information for optimization Reduced number of decision-making units Central source of information	Reduced speed (as a result of managing many tasks) Reduced speed (as a result of variety) Single point of failure Difficult to modify / reconfigure
Proper Hierarchical	Phased introduction possible Redundancy of components for fault-tolerance Cost reduction through multiple, smaller, control systems Greater information processing capability through multiple systems Faster response time Complexity reduced, responsibility and authority limited	Potential for unreliability in communications links Potential for delays in communications Difficult to modify / reconfigure structure Potential of failure at one level to halt all lower levels
Modified Hierarchical	Phased introduction possible Redundancy of components for fault-tolerance Increased autonomy of manufacturing entities Management by 'exception'	Potential for unreliability in communications links Potential for delays in communications Difficult to modify / reconfigure structure Increased reliance on local data processing
Heterarchical	No supervisor; entities dynamically co-ordinate themselves Containment of faults within entities Reduction in system complexity Opportunities for modularity and extendibility Development cost reduction	Complexity in coordinating global system Reliance on communications links Potential for deadlock

Table 1: Comparison of control architectures

Control in Industrial Additive Manufacturing Systems

Consideration of control from a manufacturing systems perspective requires that attention is given to all system resources, not just individual machines. There is, however, a dearth of knowledge considering Industrial Additive Manufacturing Systems⁷, and of the very few studies that consider control for Additive Manufacturing (personal or industrial), the emphasis is on technical implementation of control for individual machines, with no attention given to overarching control for the system. The established literature suggests that in implementation, Additive Manufacturing may be delimited as having either centralized or decentralized approaches:

Centralized architectures as demonstrated by Nagel and Liou³² focused on control from the perspective of electrical or mechanical control, including programmable logic controllers, original equipment manufacturer integrated systems, and ‘do-it-yourself’ systems produced by the manufacturer for individual machines. Similarly, Espalin et al.³³ 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. Hu and Kovacevic³⁴ demonstrate the achievement of closed-loop control for an individual machine, though this potential is technology specific: in related work for 3D printers, Hoske³⁵ notes that a lack of feedback from the machine processes inhibits closed-loop control of individual machines. Whilst all of these studies may be useful for ensuring individual machines perform their tasks, they lack the integration with many other system resources necessary for whole system control.

Decentralized architectures (typically defined in the Additive literature as ‘web-based’), consider system control as being centered on Internet-based ‘tele-control’^{36, 37} in which the control of the physical manufacturing processes is achieved remote to the physical machines. Again, this focus is typically at the machine level, though there is 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 the current study, highlighting the emergent nature of the concept and the need

for exploratory work to better understand the opportunities for Industrial Additive Manufacturing Systems.

Control Architectures for Sustainable Manufacturing

Sustainability is often considered in terms of three fundamental components (or pillars): economy, society, and environment³⁸, and general manufacturing research has typically explored opportunities to improve one or more of these.

For Additive Manufacturing, emphasis in sustainability research has principally focused on environmental and economic benefits including reducing the material content of products³⁹, increasing product longevity⁴⁰, lessening the usage of hazardous materials⁴¹, or reducing energy consumption in manufacturing^{42, 43}. Notably, economic arguments (e.g. cost savings from lower material usage) are often intertwined with environmental advantages (e.g. less materials needed from the environment). Societal issues are relatively under-explored in the literature, though these tend to focus on improvements to quality of life that arise from Additive Manufactured products⁴¹. These are all valuable contributions, and help to show how Additive Manufacturing may promote sustainability because of the unique characteristics of the manufacturing processes.

To-date, academic consideration of control architectures for sustainable manufacturing has been very limited⁴⁴, and this deficiency extends to Industrial Additive Manufacturing research for which there has been no explicit attention. This is an important omission, since whilst process characteristics may be more readily identifiable as supporting sustainability, it is important to also consider the way in which these are controlled from a systems perspective. Control is a fundamental consideration for any manufacturing system^{12, 14}, and poorly controlled systems are wasteful (in terms of time and resources), which negatively affects economic and environmental sustainability. Moreover, control is particularly pertinent for sustainability research since it underpins how a system responds to change¹³. Sustainable manufacturing achieves its positive benefits for the economy, society, and the environment by minimizing business risks and maximizing new opportunities from the improvement of products and processes⁴⁵. These actions require the system to be able to change in response to

opportunities and threats from sources both internal and external to the organization. The achievement of effective control is therefore a fundamental characteristic of sustainable manufacturing systems, both in stable and changeable conditions, and the choice of control architecture may make a relevant contribution to the achievement of sustainability in manufacturing.

Research Method

This study examines the control architectures employed in contemporary Industrial Additive Manufacturing Systems, using the four existing control architectures of Dilts et al.²⁴ as a starting point for the research. Through empirical investigation, the intention was to understand how well existing theories for ‘conventional’ manufacturing systems applied in this context, and where there was deviation arising from these technologies. This has been achieved by evaluating real-world Industrial Additive Manufacturing Systems in terms of these established architectures, and looking for alignment and disjunction between theory and practice. This aligns well to the abductive approach taken in this study, through which empirical observation is matched with theory, and from which new theory can be developed⁴⁶.

A multiple case study approach is taken in this work, motivated by the desire to understand ‘how’ and ‘why’ control architectures are employed in contemporary practice⁴⁷. By using twelve in-depth case studies (table 2), a richer understanding can be achieved than is possible from a single case⁴⁸. A diverse range of cases was chosen from a range of different application sectors, with different volume and responsiveness requirements. Data for these case studies was gained through interviews and process observation at three manufacturers employing Industrial Additive Manufacturing (table 3), supported by supplementary archival and process data provided by the companies. A case study protocol was employed to promote reliability, and methodological triangulation employed to promote validity⁴⁹. Such use of qualitative methods is consistent with this type of exploratory research, where theories are suggested through open-ended enquiry⁵⁰.

Case No.	Additive Mfr	Product Description	Process	Customer Industry	Volume (annual)	Variety	Manufacturing leadtime	Manufacturing Strategy
1	A	In-The-Ear (ITE) Hearing Aid	DLP	Medical	Tens of thousands	High	1 day	Make-to-order
2	B	Replica timbers used in the creation of a model medieval ship	LS	Archaeological	700 (in 10 batches)	High	2 weeks / batch	Make-to-order
3	B	Scale models of ancient stone monuments	LS	Archaeological	4	High	2 weeks	Make-to-order
4	B	Architectural scale models of complex shaped buildings	LS	Education	20	High	1 week	Make-to-order
5	B	Hydroform tool inserts to be used in the production of exhaust systems	LS	Automotive	1	High	2 weeks	Make-to-order
6	B	Inspection fixture for prototype toothbrush	LS	Consumer Goods	1	High	1 week	Make-to-order
7	B	Functional prototype of an exhaust sensor tool	LS	Automotive	3	High	1 week	Make-to-order
8	C	Customized surgical guide	LS	Medical	Tens of thousands	High	3 weeks	Make-to-order
9	C	Customized lighting product designed by customer via website	LS	Consumer Goods	Hundreds	Medium	1 – 2 weeks	Make-to-order
10	C	Standardized lighting product designed by professional designer	LS or SLA	Consumer Goods	Hundreds - thousands	Low	2 weeks	Make-to-stock
11	C	Hybrid fixture system customized for user application	LS	General Manufacturing	Hundreds - thousands	Medium	3 days	Make-to-order
12	C	Designer furniture	LS	Consumer Goods	1	High	1 week	Make-to-order

Table 2: Summary of case studies explored in this research

Manufacturer	A	B	C
Employees	150	5	1000
Ownership	Private	Private	Private
Years using Additive Manufacturing	>15	>20	>25
Operations	Europe	UK	Worldwide
Focal Market(s)	B2B Audiology and hearing aid products	B2B Industrial prototyping Concept designs Low-volume & customized products	B2B & B2C Industrial prototyping Concept designs Specialist medical Specialist industrial Consumer products

Table 3: Overview of participating companies

Results

The research identified evidence for the application of each of the four control architectures in contemporary practice. These are explored in turn within this section based on the characteristics identified in the literature review, using four criteria which reflect the ability to control change within the manufacturing system to support the achievement of sustainable manufacturing practice. Table 4 provides a summary of the identified control architectures, using three criteria originally prescribed by Dilts et al.²⁴ to highlight the implication of these for operations:

1. 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.
2. Extensibility is the ability for existing elements of the system to be modified, for example in the extension to include new components.
3. 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 independence of other elements within the system.

Each of these criteria affects the changeability of the system, whether in terms of making changes (reconfigurability and extensibility), maintaining stability in changing circumstances (fault tolerance), or a combination of the two (autonomy). These criteria therefore have the potential to affect the achievement of sustainability for Industrial Additive Manufacturing.

In recognition of the way in which Additive Manufacturing is deployed in real-world commercial environments, a systems perspective is taken in the assessment of control. In these situations Additive Manufacturing technologies typically co-exist with other resources of the manufacturing system (e.g. machines, labour, information resources etc.), all of which come together to satisfy demand⁷. Such a systems emphasis is beneficial in promoting 'wholeness' in evaluation⁵¹ and is also consistent with some existing perspectives on sustainable manufacturing⁵².

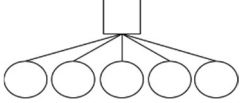
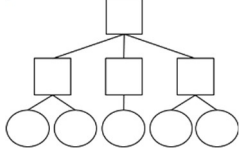
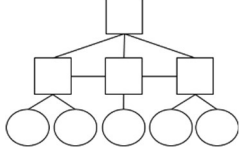
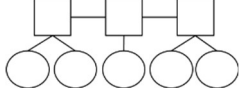


Mfr & Case(s)	Control Architecture	Reconfigurability	Extensibility	Fault Tolerance	Manufacturing Autonomy
B 2 - 7	<p style="text-align: center;">Centralized Form</p> 	Low	Low	Low	Low
A 1	<p style="text-align: center;">Proper Hierarchical Form</p> 	High	Medium	Medium	Medium
C 8-12	<p style="text-align: center;">Modified Hierarchical Form</p> 	High	Medium	Medium	Medium
C Collaborative	<p style="text-align: center;">Heterarchical Form</p> 	High	High	High	High
<p style="text-align: center;">Control component  Manufacturing entity  Control interrelationship ---</p>					

Table 4: 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 focus 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 Webber⁵³ 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. This effectively creates a new 'virtual organization' for the firm. 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.

Discussion

The results of the previous section demonstrate the different approaches taken in the control of manufacturing systems, and highlight relative implications of these to current manufacturing practice. The most notable finding of this research is the way in which the emergent technologies of Industrial Additive Manufacturing readily align to well-established control architectures prescribed for ‘conventional’ manufacturing systems. Whilst there has been much emphasis on the disruptive potential of these technologies⁵⁴, this study shows that in commercial practice, the control of these technologies does currently follow many of the existing principles of manufacturing systems control. There are, however, three specific aspects of the research that merit specific note in a sustainability context as a result of recent and on-going research:

1. Control architectures are established at a company, rather than product level.

Although the three manufacturers demonstrate a wide range of different products, technologies, and applications/customers in the focal cases, in practice control architectures were shown to align relatively well to the organizational structures of the companies. This is an interesting finding, since it runs somewhat contrary to other strategic decisions typically made by manufacturers that focus on individual products. For example, selection of manufacturing processes⁵⁵ and supply chains^{56, 57} are well-established as focusing on individual products. These approaches focus on the selection of the best options to compete in challenging markets, yet this philosophy appears not to have extended to the choice of control architectures in the focal cases.

Selecting control architectures based on the focal products to be produced may well have advantages for sustainable manufacturing. For products that have considerable demand fluctuations (e.g. because of seasonality), choosing an architecture that supports extensibility could promote economic sustainability by allowing the system to grow or contract with demand. Alternatively, for some products it can be desirable to manufacture them in close geographic proximity to actual demand (thereby reducing the effect of transport) which can promote environmental sustainability. In these circumstances control architectures that support autonomous manufacturing may be appropriate. Finally, for products that make a major improvement to quality of life (e.g. healthcare products used in surgery), confidence in their timely availability is important when scheduling surgical procedures. To achieve this contribution to the societal pillar of sustainability, choosing architectures that promote fault-tolerance supports on-going production despite

faults that might otherwise delay production, ensuring the patient receives their beneficial healthcare product on schedule.

2. Industrial Additive Manufacturing Systems rely on humans for their control.

Compared to what might be expected in a typical ‘conventional’ manufacturing system, this research highlights a significant lack of computer control and an over-riding reliance on human intervention in the control of the system. Whilst emphasis in the literature has long prescribed the application of computers in the production and control process without which control would be “inconceivable”⁵⁸, in practice only rudimentary use of computers for such activities was identifiable. Consistent with Hoske³⁵ this study found very little automated feedback from individual Additive Manufacturing machines. In most cases, the machine manufacturers did not provide suitable interfaces that could be utilized by the focal companies, which in turn impacts the ability for computers within the control system. This was compounded by the very manual nature of preparation and post-processing activities, for which automated feedback would be difficult to implement. Given the ‘high-tech’ nature of the technologies this reliance on humans for control does seem anomalous, however in future this is likely to lessen. Whilst machine manufacturers are often reluctant to provide access to machine control systems⁵⁹, multiple research projects are currently ongoing to mitigate this problem. As human involvement is lessened and real-time computer control is increased, accuracy and efficiency benefits in production may yield many positive contributions to the three pillars of sustainable manufacturing. These benefits could lead to improvements in waste production (economic and environmental), greater output from manufacturing systems (economic), and product improvements arising from accuracy that positively impact on quality of life (societal).

3. Industrial Additive Manufacturing Systems may exploit other control architectures in the future.

Whilst this study has shown a strong alignment to the well-established control architectures, it is acknowledged that alternative approaches have been developed for manufacturing systems as increasing requirements for flexibility, robustness, responsiveness, and configurability challenge the suitability of the traditional centralized and hierarchical control architectures⁶⁰. Since Industrial Additive Manufacturing is often prescribed for these more demanding production requirements, a change in architectures is a feasible proposition. For example, holonic architectures effectively maintain hierarchical control structures, but with the autonomy afforded in herterarchical approaches²⁶ and the benefits of co-operation⁶⁰. Such manufacturing control systems comprise of software and physical manufacturing models, allowing each holon to reason, make decisions, and enjoy interactive communication with other holons⁶¹.

Whilst there is little research that explores how these control architectures may affect sustainability, initial studies are positive about the opportunities. For example, Trentesaux and Giret⁴⁴ identified that holonic and multi-agent architectures are well-suited to sustainable manufacturing, but note little research has focused on the societal and environmental pillars of sustainability. They suggest that holonic control could be

used to prioritize sustainable attributes within the decision-making process, which in turn would support improvements in sustainability. Whilst such research is in its infancy, it is reasonable to consider how this could be extended to sustainability for Industrial Additive Manufacturing Systems in the future. For example, control holons could focus on prioritizing decisions to most effectively manage resources to optimize material or energy utilization, promoting benefits for environmentally sustainable manufacturing. If such architectures gained commercial traction for Industrial Additive Manufacturing, future investigation by researchers may find additional opportunities to further support sustainably through choices in such control architectures.

Conclusion

Control architectures directly affect the flow of control and monitoring information, and the interaction of the manufacturing process components²⁴, and are therefore well-established as being important for management of any manufacturing system. For sustainable manufacturing, the design of control architectures is a major (but largely unaddressed) issue for research⁴⁴. This paper therefore makes an initial contribution by examining the concept of control architectures for Industrial Additive Manufacturing Systems in this context, focusing on the underlying linkage between control and change in sustainable manufacturing.

Building on the existing theory of control architectures for contemporary manufacturing systems, this paper has demonstrated four different control architectures that have been implemented in commercial Industrial Additive Manufacturing Systems. In doing so, this paper provides an empirical evaluation of real-world production, together with a detailed discussion on the characteristics of individual implementations. Through an investigation of trends in the contemporary research, this paper has extended these current observations to highlight feasible future advances for sustainable manufacturing which may become increasingly important as Industrial Additive Manufacturing Systems become more commonplace in the production environment.

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