Introducing AM to operations and supply chain management: no sustainability benefit or virtuous knock-on opportunities?

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1. Introduction

Additive manufacturing is a technology that makes it possible to directly produce parts from digital design models using additive production processes. The introduction of AM in manufacturing supply chains can be approached as an evolutionary design problem (Langlois 2003): How AM is initially introduced in operations affects requirements for the future development of AM technology, as well as what opportunities open up for designing and managing supply chains in new ways. In this situation, when both the manufacturing technology and supply chain application side of the equation are undergoing change it is challenging to evaluate potential effects on sustainability. Nevertheless, we will make an attempt to identify key problems for improving sustainability outcomes. In this column we will focus on the problems that AM enabled practices potentially address, and the impact of introducing AM on that problem, considering the current state of AM technology.

Supply chains are sets of interdependent economic actors whose relationships can be designed and operated in different ways to deliver products to a market. Supply chains can be designed to align the operations of the actors and improve the performance of the system in terms of delivery time, cost, quality, flexibility and increasingly also for social responsibility and environmental benefit. In this column we consider both the design that locates and links production, warehousing, distribution and sales; and *planning and execution* that creates the plans, orders, and replenishment mechanisms used for communicating between demand and supply.

2. Four ways for AM enabled Supply Chains to improve sustainability¨

Current AM enabled practices support – rather than revolutionize – established operations and supply chain management. The most widely established practices are prototyping, followed by parts production, and tooling.

One problem that AM enabled prototyping and tooling addresses is the slow and drawn out processes for new product development and introduction. This is a problem that is generally *not* relevant to the goal of sustainability. Introducing AM in prototyping improves the capability to iterate designs using physical objects, while in tooling it allows for faster and cheaper production engineering and re-tooling.

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However, in as much that tooling could be considered a product in itself, for example for a tool making firm, some of the benefits mentioned in the next section could accrue.

The use of AM for final parts enables on-demand parts manufacturing, and on-demand changes of those parts (e.g. modifying the shape and weight of parts for the context of use). Based on additive final parts manufacturing it is possible to identify four ways that operations and supply chain management can contribute to the goal of improving sustainability. These are reducing transportation, reducing material use, extending the life of products in use and, upgrading and refurbishing products in use. AM enabled supply chain practices address these problems by:

- Reducing transportation through localizing production (and local employment)
- Reducing material consumption through reduced over production and in some cases simplified production operations
- Extending the life of products in use with additive repairs and on-demand spare parts
- Upgrading and refurbishing products in use with improved parts and components

Next we will evaluate the four ways of AM to improve the sustainability outcomes of operations and supply chain management practice. We focus in particular on the constraints of AM that might bear repeating in the middle of the current hype. The review article by Karel Kellens (this issue) highlight three important challenges facing AM in final parts production from Khajavi at al. (2014): the slow speed, high equipment cost and significant need for post processing.

2.1 Reducing transportation through localizing production

A way to reduce transportation is to locate parts production closer to the point of assembly. Localizing parts production reduces the transportation of sensitive finished parts while it increases the transportation of more compact raw materials. The positive environmental effect assumes that transporting raw materials in bulk is more efficient than transporting finished parts.~~, but uncertainty in production may require larger bulk materials inventories.~~

Localized AM parts production assumes simplification, substitution for conventional manufacturing, and deskilling. But the current state of AM does not yet satisfy these assumptions. There is some simplification of the manufacturing process especially when we want to make complex items, but there is an inherent conflict between the production rate for AM and need for post-processing. Faster processing (such as Cincinnati Corp /Oak Ridge National Lab's Big Area Additive Manufacturing (BAAM) technology) generally leads to poorer surface finish and hence a larger need for post-processing, which requires specialized manufacturing and skills which may push back against localized prodution.

Perhaps the most challenging post-processing from a supply chain perspective is assembly. Reducing transportation by shifting manufacturing closer to the market assumes that not only parts production can be localized, but also assembly. In other words, in addition to parts production not requiring specialized tools and skills, also assembly should be simple and not require specialized tools and skills. This would hold for products such as IKEA furniture that are specifically designed for simple assembly – but does not hold for more complex products, and products not designed for easy assembly.

Leveraging the opportunity offered by AM there is potential for the integration of parts needed in assemblies, thereby potentially significantly simplifying the supply chain.

Localization of production is inhibited also by the high cost of equipment. A further development of the localization practice that can possibly address this issue – and the issue of skill requirements for pre and post processing - is sharing AM capacity in localized manufacturing hubs. The potential benefit of shifting manufacturing to a common hub depends on increasing capacity utilization, and reducing the cost of capacity buffer. A local hub would also provide benefits in terms of more efficient raw material transportation, but would increase transportation of finished parts. In fact, this type of local manufacturing hub is similar to city logistics terminals in seeking both the benefits of localization and centralization.

2.2 Reducing material consumption through reduced over production

AM enabled practices can also reduce material consumption. The mechanism is on-demand production that reduces the risk of producing parts to inventory that will never be used. From an operations and supply chain perspective the risk for inventory obsolescence derives from engineering changes (changing the specification) or lack of demand (e.g. a spare part that is never needed). Thus, on-demand production can potentially reduce material consumption in the product introduction phase when engineering changes are more likely, and in the end-of-life phase when the risk for spare parts obsolescence increases.

When many parts are required within a short lead-time, the slow speed of production in AM limits the usefulness of on-demand production. Inventory buffers would be needed, which increases the risk of obsolescence and reduces potential benefits in reducing material consumption. Slow speed of production also limits the usefulness of localization if lead time requirements are short and AM cannot be used on-demand.

However, with sufficiently generic AM capacity on-demand production can be used to eliminate batching and inventory created through batching. On-demand production and elimination of batches is combined in the practice of direct kitting. Parts needed for a specific product are produced to demand as kits. This reduces in addition to inventory, also the need for warehousing and handling. The practice of direct kitting somewhat reduces the challenge of slow speed of AM. Producing a kit of parts using AM is in many situations much faster than producing batches of conventional parts and handling those batches in preparation for assembly. Thus, the slow speed of AM production is compensated by the ability to produce without batching.

2.3 Extending the life of products in use with on-demand spare parts

Equipment manufacturers typically support products in use for only a limited time. The reason for this is that it is very expensive to have all spare parts in inventory.

Introducing AM for producing spare-parts one-off, and on-demand potentially extends the time an original equipment manufacturer can support products in use indefinitely. However, this practice is constrained by the large number of spare parts that cannot be produced using AM without a significant effort in re-designing for AM and on-demand production. Thus, the additional need for pre-and post-processing is not in manufacturing for this practice, but in design. Finally, for most products in use it is likely impossible to redesign all parts for on-demand production.

Furthermore, the sustainability outcome of this extension is not self-evidently positive. Life-cycle extension could for example keep less energy efficient equipment in use longer and slow down the renewal of the installed base (Gutowski 2011).

2.4 Upgrading and refurbishing products in use with on-demand improved parts

Radical improvement of sustainability impacts usually requires major changes in the product. The new more energy-efficient product usually has a completely different architecture, e.g. radial to bias ply tires, desktop to laptop computers, CRTs to flat screen displays, top loading to front loading dishwashers (Gutowski 2011). The practice of introducing such changes is a refurbishment project, which is currently used mainly for expensive equipment and systems with long life-cycles, and usually the goal is restore to "like new" quality. An excellent example of this is included in this issue, see Walachowicz et al 2017.

However, AM may enable a new practice of incremental and continuous improvement of products in use for some types of products. For example, on-demand optimization of part design and material use is in principle possible using the combination of part design optimization and AM. For parts in moving equipment efficiency could be improved by replacing bulky parts with lighter parts – either using new lighter materials, or lighter structure – or both. Martin Baumers in Nottingham has recently been looking at this for aerospace (Baumers et al. 2016). In a more limited extent this could apply for any moving equipment, for example for elevators where new lighter rope technology can have a dramatic effect. However, this assumes that the safety issues related to continuous change of a product in use can be addressed. You can't change critical components in products such as aircraft or elevators without extensive testing, which undermines the potential of a new practice of continuous improvement of products in use.

3. Discussion

There are three challenges when assessing the potential environmental implication of a new technology. The first is estimating the potential success and eventual form of the new technology. The second is estimating the manner of the implementation relative to other competing technologies, for example will it substitute for, or complement other technologies. And the third is the environmental evaluation of the implemented new technology. In this column, we have evaluated two technologies, covering not only the state of the art of additive manufacturing, but also operations and supply chain management using additive manufacturing.

We consider the introduction of AM in operations and supply chain management as an evolutionary design problem (Langlois 2003). We are interested in how AM is initially introduced and how this affects the paths that open up for designing and managing supply chains in more sustainable ways. We found that the most common way of introducing AM for prototyping and tooling does not open up significant opportunities. On the other hand, introducing AM for parts production opens up several paths for reducing environmental impact: localizing parts production, on-demand production, and upgrading and refurbishing products in use.

Considered separately, we expect none of these paths to have a major environmental impact. Reduced transportation from localizing parts production is constrained by the need to transport raw materials and consolidating further processing – such as assembly - in central locations. Reducing material consumption through less overproduction is constrained by the slow speed of AM and the need for inventory to compensate for this slowness. Only early in product introductions, and at the very end of the product life cycle is AM likely to be used in ways that reduce the risk of overproducing parts. Finally, employing AM to extend the lifecycle of products in use, and to upgrade small populations of products in use is constrained by the need to redesign parts for AM.

Considering the paths opened up by AM in parts production all together yields a more positive assessment. In some situations we may see additional paths for reduced environmental effects opening up as virtuous knock-on opportunities from taking a first path (Baumers et al. 2016). For example, spare parts originally designed for conventional methods need to be redesigned for on-demand production using AM. In this situation knock-on opportunities are simplified logistics and handling, as well as light-weighting to reduce energy consumption in-use. It is a small added effort to take environmental factors into consideration when redesigning a part in any case. In a similar way, localizing parts manufacturing is an opportunity to also consider ways to simplify and fool-proof assembly and other post-production activities, which in turn reduces the need for transportation of parts and assembled products.

We have tried to identify the areas of potential environmental benefit by the exploitation of additive technology in an environmentally improved supply chain. Future research should explore both specific paths individually and together, evaluating both constraints and potential virtuous knock-on scenarios. At the moment however there are many moving parts to this problem. According to the ISO/ASTM Standard 52900:2015(E) there are 7 different process categories for additive technologies, but there are many varieties within each category, and many new technologies and variations being developed every day. On the operations and supply chain side there are also many operational practices and business models relying on Additive Manufacturing.

For operations and supply chain management, AM is a tool to reduce the transaction costs in manufacturing by the ability to go more directly from design to solid object. Benefits are most visible for small, unique and complex objects. To date, perhaps the most widespread use of AM in the supply chain has been in the customization of medical applications, such as hearing aids and teeth aligners. This use has not yielded any significant environmental benefits that we know of. However, there has also been success in using AM to redesign and refurbish a fighter-jet to significantly extend the life-cycle of the product in-use.

Any particular attempt to use AM in innovative and disruptive ways in the supply chain may or may not be successful. If history is our guide, many promising paths will initially fail to produce results and we will need to learn from this failure to focus efforts on the right settings and use cases. When viewed as a tool, one sees AM could be used in many ways, both good and bad. The outcome will depend strongly on the intentions of society, and the incentives put in place to obtain the desired outcomes. If no new incentives are initiated, it is quite possible that the ultimate outcome of lowering the transaction cost for manufacturing, will just be more manufacturing with no environmental benefit whatsoever.

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