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Comparison of production strategies and degree of postponement when incorporating additive manufacturing to product supply chains

J. Minguella-Canela[a]*, A. Muguruza[a], D.R. Lumbierres[b], F.-Javier Heredia[b], R. Gimeno[c], P. Guo[d], M. Hamilton[d], K. Shastry[d], S. Webb[d]

[a]*Universitat Politècnica de Catalunya - BarcelonaTECH, Centre CIM, C/Llorens i Artigas, 12, 08028 Barcelona, Spain*
[b]*Universitat Politècnica de Catalunya - BarcelonaTECH, DEIO, FME, C/Pau Gargallo, 5, 08028 Barcelona, Spain*
[c]*Accenture Analytics, Pl. Xavier Cugat, 2, Edifici B, 08174 Sant Cugat del Vallés, Spain*
[d]*Accenture Technology Labs, 50 W San Fernando St., San José, California, USA*

Abstract

The best-selling products manufactured nowadays are made in long series along rigid product value chains. Product repetition and continuous/stable manufacturing is seen as a chance for achieving economies of scale. Nevertheless, these speculative strategies fail to meet special customer demands, thus reducing the effective market share of a product in a range.
Additive Manufacturing technologies open promising product customization opportunities; however, to achieve it, it is necessary to delay the production operations in order to incorporate the customer's inputs in the product materialization.
The study offered in the present paper compares different possible production strategies for a product (via conventional technologies and Additive Manufacturing) and assesses the degree of postponement that it would be recommended in order to meet a certain demand distribution. The problem solving is calculated by a program containing a stochastic mathematical model which incorporates extensive information on costs and lead times for the required manufacturing operations.

Keywords: Additive Manufacturing; Ultra-postponement; Supply Chain

* Corresponding author. Tel.: +34-93-401-7171; fax: +34-93-401-7170.
E-mail address: jminguella@fundaciocim.org

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1. Introduction

Additive Manufacturing (AM) technologies are a broad set of very promising methods and tools capable to deploy unit-to-unit mass customization and to materialize product manufacturing just in the time and place where demand occurs. The first AM technologies have been available over more than thirty years; and so they are starting to be mature. However, the introduction of AM across the Product Value Chain is still uneven over the different product stages.

Having a look at the early stages of product development (conceptualization, early design, prototyping and testing), at the present time it is possible to state that most of the companies in the industrial sectors duly apply AM technologies to achieve better results. Moving a bit forward to manufacturing stages, many industrial companies use AM for tooling and parallel applications but few companies use AM to materialize the product itself. Furthermore, when arriving to the distribution and point-of-demand application, only very few incipient industry cases use AM to bring value to the product. And finally, when arriving to the end-of-life product stages, even less cases can be found where the material recovery aims to AM reprocessing activities.

The reasons for this unequal application are both technological –some materials and part’s requirements cannot still be meet with AM technologies where in other applications complexity can be meet seamlessly- as well as of economical competence –manly related to the value-added product niche and the cost level achieved-. Building into these ideas, the present study focuses on the importance of delaying production respect the moment when the demand occurs thanks to AM technologies and the implications of this approach to the entire product value chain competitiveness.

1.1. Structure

As commonly introduced in the literature, a particularly relevant way to improve the efficiency of a product deployment value chain is to postpone any changes in the product to the latest possible moment. When applying this rationale to design, manufacturing and distribution strategies, the concept of postponement relates to the matter of delaying the supply chain processes as much as possible to the moment of the customer purchase, in order to incorporate the maximum features requested by the clients; whilst meeting the supply chain delivery times required.

On the contrary, as opposite approach, the speculation concept relates to the advancement of all transformation activities to the earliest possible moment, much before the demand occurs, in order to reduce product costs and to capture a specific demand forecasted in advance.

The moment in time where the acquisition of the product by a customer happens is referred as the Customer Order Decoupling Point (CODP)[1] and serves as a milestone from which the part design is considered as frozen. In this way, the CODP specifies the position in the product value chain where the postponement occurs. As a consequence of postponement, as introduced by Yang et al.[2], when the CODP moves upstream, the effectiveness and flexibility of the supply chain gets enhanced.

In the general case, companies need to know in which degree for each case is preferable to use some postponement supply chain strategies in the short and in the long term. In particular, with the introduction of additive manufacturing technologies to the range of manufacturing possible strategies to manufacture a product, the assortment of possibilities expands and the solution of the problem increases in complexity; thus requiring a knowledge-intensive mathematical approach.

The impact in the supply chain of delaying the production start to the moment when the demand occurs has been addressed by authors by constructing analytical models [3] and by optimizing the product allocation of resources [4], [5]. The studies combining of the impact in the supply chain of ultra-postponement plus the use of 3D printing technologies are revealing that it will change the way the goods are produced. This conclusion is inferred after performing quantitative analysis comparing total supply chain costs of using 3D manufacturing versus classical manufacturing in different companies [6], [7] and by identifying specific business areas of impact of 3D printing in relation to other supply chain strategies [8].

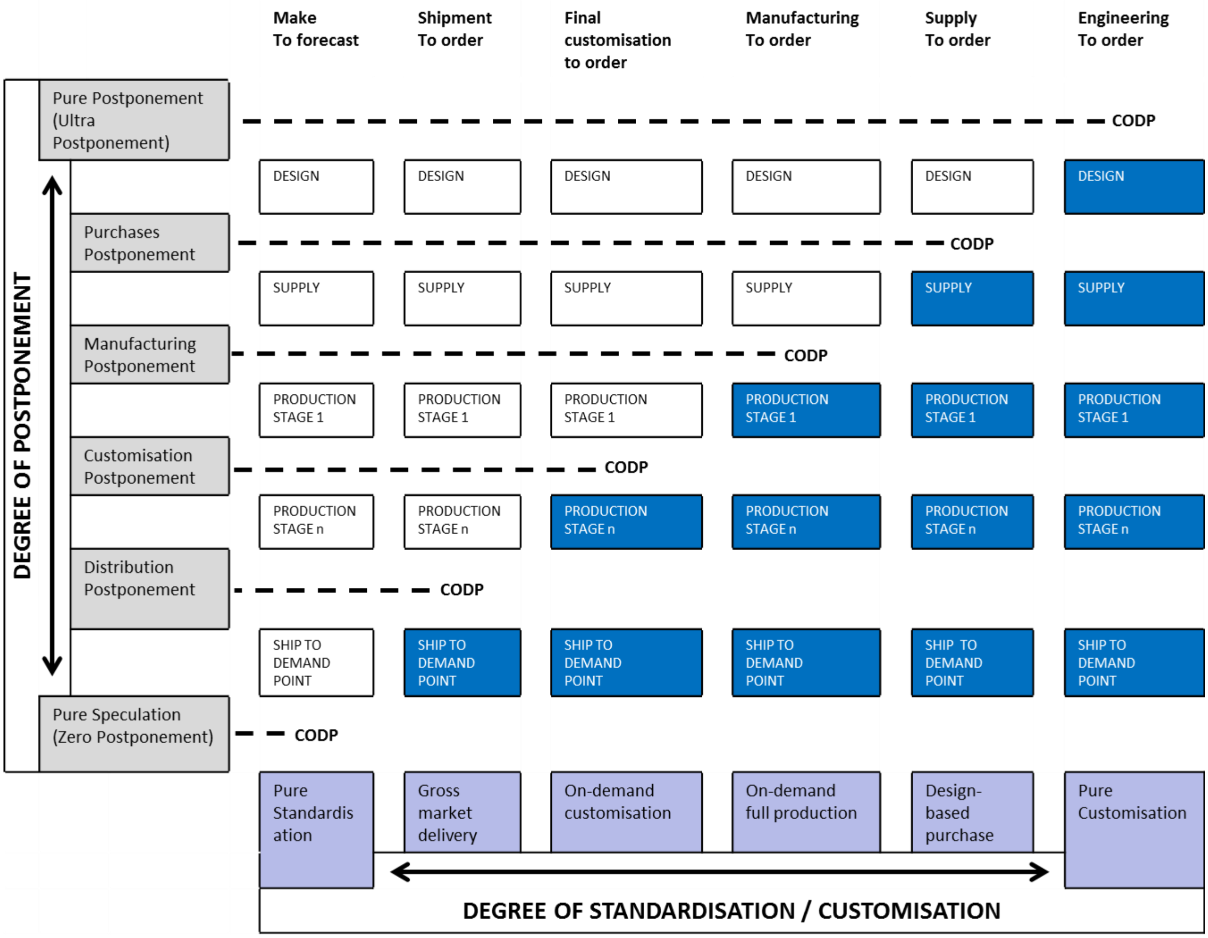

Fig. 1. Schematic representation of the CODP position in different situations along the value chain. Elaborated by the authors from the findings of the study of Yang et al. [2].

1.2. General objectives and study conducted

The present study analyses 4 use cases of real products that could be manufactured via several different processes; one of those processes being an AM commercially available technology.

For each use case and possible manufacturing strategy, the different production processes are evaluated in terms of (i) Graph of operations needed for the manufacture of the product, (ii) Cost analysis of the different blocs contained in the graph and in particular of the AM operations needed and (iii) Construction of a Numerical optimization Model for the comparison of outcomes provided by the different manufacturing strategies.

For each product assessed, certain parameters are evaluated (e.g. volume, height, material) and certain constraints are indicated (e.g. demand in units, degree of personalization). Under these scenarios, the numerical modelling outcome offers the Best CODP -per product and scenario- or the Best AM strategy for a certain CODP.

2. Supply chain process composition

Taking into consideration that all products included in the present study are currently in production via technologies different than AM, for all products there have been analyzed at least two different strategies for their materialization. Also, depending on the specific part to be manufactured, in some cases several AM strategies are feasible options –both technologically and in localization/delocalization conditions-, so more process variations arise. All possibilities taken into account in the general model aim to enhance a high level of modelling flexibility.

2.1. General framework modelling of production strategies

Concerning the production characterization, intensive work has been undertaken to depict the AM technology-driven costs, in order to generate a comprehensive cost function for each technology assessed in the study. The costs taken into account in the modelling are:

- (C1) Machinery acquisition costs, incorporating the periodical maintenance activities required
- (C2) Raw material costs
- (C3) Energy consumption costs
- (C4) Labor costs associated to the use of each technology (both for the technological use and/or in the post-processing activities)

Also, factors affecting the supply chain costs due to the degree of production delocalization (transport, stocks, facilities and administration) have been described. In this case, it has been considered that the manufacturing stage can be decided to be implemented in up to six different production facilities locations, depending on the distance to the final use point. These locations and their implications on the distribution schema are:

- (L1) Location 1: Far continent manufacturing site, normal shipping mode
- (L2) Location 2: Far continent manufacturing site, urgent shipping mode
- (L3) Location 3: Same continent manufacturing site than production happening
- (L4) Location 4: Service bureau as manufacturing site with short delivery times
- (L5) Location 5: In-store manufacturing mode
- (L6) Location 6: Manufacturing in the customer home

Due to the different location possibilities (L1-L6), some extra costs have to be incorporated in the modelling, namely:

- (C5) Stock holding costs
- (C6) Delivery costs

2.2. Particular Additive Manufacturing technologies reviewed

In order to broaden the product range that could be covered by the present study, there has been an intensive AM technology costs review so to be able to introduce in the model products manufactured in the broader materials range; i.e.: plastics, metals and ceramics. To this respect, the cost modelling included the following technologies:

- (M0) Conventional manufacturing technologies (i.e.: original process, no AM))
- (M1) Plastic Filament Processing technologies (Fused Filament Fabrication, FFF)
- (M2) Plastic Sintering Processing technologies (Selective Laser Sintering, SLS)
- (M3) Plastic Jetting technologies (Polyjet and Multi Jet dropping, DoD)
- (M4) Plastic Resin Processing technologies (Direct Light Printing, DLP and Stereolitography, SLA)
- (M5) Metal Sintering Processing technologies (Selective Laser Melting, SLM)
- (M6) Ceramic Processing technologies (Ceramic deposition)

3. Mathematical modelling of the product supply chain

The mathematical formulation of the product value chains modelled in the present work has been performed as a generic supply chain in an oriented graph G = (N, L), where nodes 'N' correspond to the operations in each production process feasible strategy and the arches 'L' represent the precedence order of the operations within a given process.

For each product, there are as many routes as the number of the possible production alternatives evaluated -minimum two, as stated above- defined by a set of the operations presented in Figure 1; namely: design, supply, 'n' production stages and distribution. Each of these operations -graph nodes- are characterized by lead times and costs parameters.

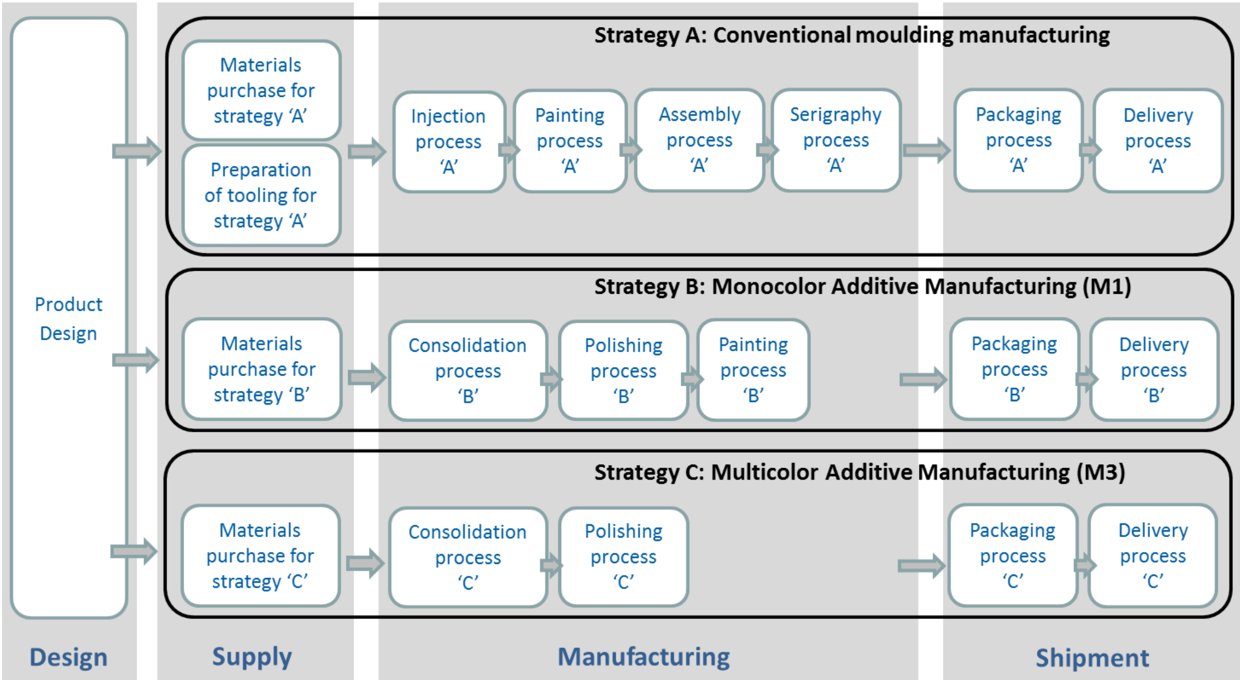

Fig. 2. Example of a Product Value Chain modelled in a graph in order to undertake the mathematical assessment. In this case, three production strategies are feasible: by conventional manufacturing technologies, by mono-color AM and by multi-color AM technologies.

Based on this graph modelling, the core development for problem solving is based on a mixed integer two-stage stochastic program that encounters (i) the optimal production strategy needed in order to be able to serve the level demand required –being the demand a parameter that can be decided by the user at the beginning of a program run-, (ii) the optimal production quantity for each operation in the product value chain and (iii) the optimal CODP for each selected strategy.

For each case, the demand level can be set as a normal distribution with mean and standard deviation (μ; σ). In the cases the demand could fell in a negative number it is considered that no demand occurs.

The experimentation conducted in the present study was performed by implementing the mathematical modelling in AMPL (AMPL, 2016) and CPLEX (CPLEX, 2016) and the models were run under Windows 10 on a i7 PC.

4. Product segments clustering and assessment in case studies

Following to the general framework for products materialization presented in the previous sections, the implications of the demand and the degree of personalization of products originate different needs in the degree of postponement required in each case. According to demand and personalization, the present study conducted a clustering of products in the four product segments depicted in Figure 3. The four product segments -exemplified via use cases- are presented and commented in the following subsections.

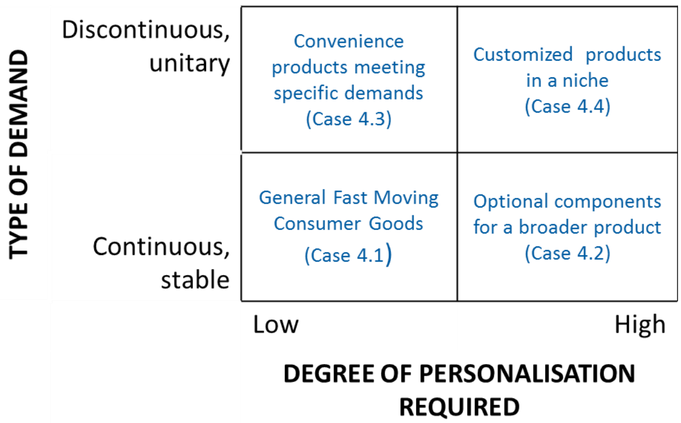

Fig. 3. Product segment clustering according to the demand level and degree of personalization of products

4.1. General fast moving consumer goods –e.g. Department store merchandising (no personalization, stable demand)

One of the paradigmatic product segments that deserve to be analyzed is the group composed by goods with a low degree of personalization and with minimum value added. Typically, the products in this segment are manufactured using pure speculative strategies, combining long production runs with delocalized manufacturing (Location L1).

For the products in this group, it has been highlighted that for some materials there is room to swap production to the "In-store manufacturing mode" (L2) or even at "customer home" (L1) in order to reduce stock and shipping costs with the current costs and technological levels of development.

4.2. Component parts for a broader product assembly –e.g. Automotive industry customization parts (high personalization, stable demand)

A second product segment of interest when analysing different value chains is composed by products that are manufactured in some early stages in large batches of a general platform which is finally customised to the customer demands once the purchase occurs. In this case, the value chain strategy is in the middle between pure speculation and pure postponement alternatives. Being the CODP at the central stages of product manufacturing improves the delivery times –as most of the functionalities are enabled in locations L1, L3 or L4 when the order occurs-, but maintains the possibility to customise some components in locations L4 or L5.

Approaching the automotive industry within these second product segment strategies could serve to apply AM technologies to achieve further product customization as the main product in the assembly (i.e.: cars) are high value-added products that could meet the customers' pricing expectations even if supplementary manufacturing costs are added to the standard products.

4.3. Convenience products –e.g. Toy industry (no personalization, discontinuous demand)

Another product segment of particular interest relates to the products that are ranged as convenience –i.e.; not of primary necessity-, which the customers purchase mainly in a discontinuous and impulsively manner –i.e.; based on personal affections and not because of its technical characteristics-. One paradigmatic case of products according to this classification is configured by the figurines that are placed on top of cakes as decoration in many celebrations and that the children play with as regular toys. Usually, products in this group are manufactured in long pure speculative runs that most of the times do not meet properly the real final demand (by excess or by defect) and that imply long delivery periods of time which impede to serve local demand short-series trends.

The assessment of the possible scenarios in the value chain of the products in this group reveals that there is a big possibility to improve the capability to adjust the production to the real demand, as well to be able to serve short series in limited periods of time. The main outcomes of the study in product segment 4.3 are commented in section 5.

4.4. Customized products in a niche – e.g. Toy industry (high personalization, unitary demand)

Finally, as a variation of the general convenience product segment, on the pure postponement strategies are placed products that are sold just as Computer Aided Design files and which have to be manufactured after being purchased. In these cases, with the incorporation of AM technologies, the production activities can swap to Locations L5 and L6 reaching the paradigm of conveying all the materialisation process in the place and time when the demand occurs.

Although at the present time only few segments of products are available to be designed and downloaded on-line for manufacturing, it is expected to appear a growing offer of these products as more content is disclosed and the user interfaces evolve to more ease to use platforms.

5. Results obtained for different study cases of a same industry (4.3 - Toy industry)

The results disclosed below refer to research findings in case studies of products in a sector with discontinuous demand -because of a classical seasonality behavior in timings like Christmas time- and even uncertain demand –due to many different factors affecting the willingness of a customer to purchase a specific character; in this case the Toy Industry (4.3).

The manufacturing process alternatives analyzed are as shown in Fig. 2, noting that different product operations could be performed in different product locations from the options presented in previous section 2.1 (L1-L6). This has effect in the costs of each operation and could possibly add more branches and possible routes to the graph

With all the data introduced in the modelling of the different product variations intensive testing was performed for up to 20 different demand scenarios.

For the cases of figurines with a very high level of demand (e.g.: 50 000 units) the results yield by the model advised to implement pure speculation and delocalized processes. Only in cases of demand with discontinuous peaks AM technologies are envisaged to bring extra production capacity.

For the cases of figurines with an average level of demand (e.g.: 20 000 units) the model analysis shows that it is interesting to run some postponement strategies when the demand uncertainty (dispersion in the normal distribution) increases. However, full postponement is not considered as a feasible option as it would be not fast enough (in terms of production lead times) to fulfil all the customers demand.

For the cases of customized figurines (unitary demand levels), the model reveals that localization of manufacturing in far locations is not a feasible option to serve the demand due to the long delivery lead times. On the contrary, bringing the manufacturing to production points close to where demand occurs is a highly recommended option which even opens the possibility to include some customization in form of product variations to the general football player’s figurines in a cost-effective manner.

6. General conclusions and future work

The model generated is broad enough to deal with products implying any number of different operations and any number of alternative production processes as it treats the product value chain flow as a graph of interconnected boxes. In each study case, the results are multi-scenario decision points for the assessed manufacturing strategies.

For each product, the model generated can be introduced in the model in two different ways. The first assessment mode is used to determine the best production strategy –from the different available scenario possibilities- for a certain product and with a certain level of demand. The second assessment mode is used to decide the best CODP for a determined production possible strategy.

Based on the results obtained in the many product scenarios run in the present study, it arises that, at the present time, AM technologies are to be maintained as a complement in manufacturing and not as a substitute for the products with low degree of personalization, low demand and/or low value-added products. However, it is clear that it will continue to increase in the ratio of use in industrial processes as (i) new AM technologies are developed –so parts could be manufactured in a bigger material range and at a faster production paces-, (ii) new cost levels are meet –so lower value-added niches can be addressed- and (iii) more design for AM procedures are adopted –so AM technologies can compete more effectively with other manufacturing technologies.

In addition to the application of additive manufacturing procedures to traditional business models, the further development of new technologies and the advances of these in terms of costs reduction and processing speed, opens new possibilities to make viable new business models and in particular business models with distributed supply chains geographically and across the product stakeholders. In these last paradigms, designer, dealer and manufacturer do not need to be part of the same entity, but can be totally independent companies and individuals. In these cases, cluster adoption of supply chain strategies could be further addressed in future works.

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