Aligning Manufacturing Strategies with Complexity Factors in the Aerospace Supply Chain

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Summary Abstract
Aerofirm is a large and vertically-integrated manufacturer providing strong and light materials mainly for commercial aerospace, but also for space, defense and industrial application. They face complexity from varying customer needs, a vast product range and a large network. Complexity at Aerofirm also arises from unsynchronized processes, this paper focuses on aligning the manufacturing strategy process. The approach proposed is to first calculate suitable strategy based on: forecast accuracy, volume variability, relative volume and supply chain depth. The results were then reviewed by key personnel to refine them based on qualitative knowledge, showing a mix of manufacturing strategies is essential.

Keywords: Supply Chain Complexity, Aerospace, Manufacturing Strategies

Introduction
An aerospace manufacturer (AeroFirm) has a complex internal supply chain with a vast product range of 20,000 different items. This product range continues to grow as customers often demand new specifications to meet their needs. Furthermore, AeroFirm has a supply chain that includes 18 different manufacturing locations where disparate processes are in operation across multiple time-zones and cultures. This paper focuses on the work being conducted to align the processes for manufacturing strategies across AeroFirm. Historically, the approach and implementation of manufacturing strategies has been defined, managed and operationalised differently across the 18 locations in Europe, USA and China. The lack of alignment of manufacturing strategies can cause several issues, including: inefficiencies, misleading prioritisation of customer orders, emergency air freight shipments and sub-optimal inventory holding.

This paper focuses on understanding the supply chain complexity factors faced by AeroFirm for contextualisation. The paper also explains the research and development of a consistent process for determining the order penetration point (OPP) and associated manufacturing strategy, from make-to-stock, assemble-to-order, make-to-forecast and make-to-order. Hence, there is an exploration of the complexity at AeroFirm and how this relates to the manufacturing strategy decision. There are two specific objectives for this paper:

1. Identify the supply chain complexity factors faced by AeroFirm.
2. Develop a process for selecting manufacturing strategy.

Supply Chain Complexity and the Order Penetration Point

Early work explored how supply chain complexity can generate demand amplification (Forrester, 1958, Forrester, 1961). Forrester (1958) stated that a "unified system" is needed to manage the five interrelated flows of "information, materials, manpower, money, and capital equipment" (Forrester, 1958, page 38). Forrester's work showed that forecasting and inventory policies used at each node of the network distort demand and this distortion is magnified as it is transmitted upstream, which leads to boom and bust scenarios. Later work is this area by Lee et al (1997) coined the term "Bullwhip effect" which they defined as "the phenomenon where orders to the supplier tend to have larger variance than sales to the buyer (i.e., demand distortion), and the distortion propagates upstream in an amplified form (i.e., variance amplification)." (Lee et al., 1997, pg. 546). They define four causes of the Bullwhip Effect: 1) Demand Signal Processing; 2) Order batching; 3) Price fluctuation and 4) Rationing and shortage gaming. Lee et al's (1997) Bullwhip Effect did pull the four phenomenon together for the first time. However, Disney and Towill (2001) trace the origins of these effects back to other previous research. Notably Forrester's (1961) work as explained earlier, Burbidge's (1991) research on impact of order batching and on rationing and shortage game effects discussed by Houlihan (1987).

Christopher (2011) identified eight main sources of supply chain complexity: network, process, range, product, customer, supplier, organisational and information complexity. Network complexity occurs as more nodes means more complexity. Process complexity is the haphazard development of processes which often mean more serial processes and more handovers. Range complexity considers how the number of different products tends to grow and the frequency of customisations. Product complexity arises when there are few common modules/sub-assemblies. The number and the differing needs of customers generates customer complexity and causes variation in cost to serve. Supplier complexity arises as the size of supplier base increases, hence, increasing relationship management. There is a balance to be struck between becoming too dependent on a few suppliers versus coordinating many. Organisational complexity refers to division of labour across functions and processes, which is more difficult when they are located in different locations, different time zones and cultures. Information complexity exists if there is a vast amount of data in separate systems which obscures visibility of actual demand.

Serdarasan (2013) reviewed and classified supply chain complexity drivers, which he defined quite simply as "any property of a supply chain that increases its complexity" (pp. 534). His classification including demand amplification (c.f. Forrester) which is one dynamic type of complexity. A supply chain can be considered as dynamic, non-predictable and non-linear and hence complex. Serdarasan (2013) also included the static complexity, essentially that any supply chain has a high number of different elements, which are also varied and interact with each other. There has been considerable research focusing on considering the difference between the static supply chain structure complexity and dynamic time and randomness complexity in supply chains (e.g. Frizelle & Woodcock 1995 and Sivadassan et al 2002). The combination of static and dynamic complexity means that there are so many factors that it becomes impossible for a human decision maker to consider all of them (Miller, 1956; Simon, 1974; Warfield, 1988). Hence, research has been conducted on how expert systems to make complex supply chain decisions (Efstathiou et al., 2002).

Serdarasan (2013) combines this consideration of type of complexity with the origin of complexity, following on from the work of Childerhouse & Towill, 2004; Isik, 2011 and Mason-Jones & Towill, 1998 to consider: internal, supply/demand interface and external complexity. Internal drivers are within the organization and include product and process decisions and factors. Internal drivers are considered easier to adapt and leverage as they are in the span of control. Supply/demand interface relate to those factors that operate in cooperation with suppliers / customers, these relate to the material and information flows between suppliers, customers and/or service providers. Hence, the ability to leverage and adapt these depends on power, trust and the nature of the relationship between the firm and the supplier/customer. External drivers are those where the firm has little or no impact on and include aspects like: market trends, political changes and so on. Some more examples of the different supply chain complexity drivers and how they can be classified is shown in Table 1 from Serdarasan (2013).

Table 1 – Some drivers of supply chain complexity. (from Serdarasan, 2013)

	According to origin		
According to type	**Internal**	**Supply/demand interface**	**External**
Static	• Number/variety of products • Number/variety of processes	• Type of product • Number/variety of suppliers • Number/variety of customers • Process interactions • Conflicting policies	• Changing needs of customers • Changing resource requirements • New technologies
Dynamic	• Lack of control over processes • Process uncertainties • Employee related uncertainties • Unhealthy forecasts/plans	• Lack of process synchronization • Demand amplification • Parallel interactions	• Changes in the geopolitical environment • Shorter product lifecycles • Trends in the market • Market uncertainties • Future developments
Decision-making	• Organizational structure • Decision making process • IT systems	• Differing/conflicting decisions and actions • Non-synchronized decision making • Information gaps • Incompatible IT systems	• Changes in the environment • Factors that are out of span of control • Uncertainty of unknown/ uncontrollable factors

This research is considering the complexity faced by AeroFirm in general, but also taking a specific focus on the manufacturing strategy decision. The decision of when to assign inventory to a customer has long been considered a strategic one (Sharman, 1984, Hoekstra and Romme, 1992, Olhager, 2003, Olhager, 2013). The term order penetration point (OPP) has been defined as "the point in the manufacturing value chain for a product where the product is linked to a specific customer" (Olhager, 2003). The position of the OPP then indicates the appropriate manufacturing strategy, as shown in Figure 1 from Olhager (2003).

Product delivery strategy	*Design*	*Fabrication & procurement*	*Final assembly*	*Shipment*
Make-to-stock	------------	------------	------------▶	OPP ——▶
Assemble-to-order	------------	------------▶	OPP ———	——————▶
Make-to-order	------------▶	OPP ———	———————	——————▶
Engineer-to-order	OPP ———	———————	———————	——————▶

Figure 1 – The Order Penetration Point and Manufacturing Strategies (Olhager, 2003)

Research in the OPP literature from Olhager (2003) identified that three complexity factors impact the lead time and thus the OPP decision: 1) market-related, 2) product-related and 3) production-related factors. Market-related factors include aspects like: delivery lead time requirements, product demand volatility, product volume, product range and customisations, customer order size and frequency and seasonality. Product-related factors include aspects like: modular product design, customisation opportunities, material profile in the bill of materials (raw, sub-assembly or final product) and breadth and depth of the product structure. Production-related factors include: production lead time, number of planning points, flexibility of the process, position of the bottleneck and sequence dependent set up times. This framework can be considered in the process of deciding on manufacturing strategy at AeroFirm. There have been several studies which have focused on determining appropriate manufacturing strategies, but, the research looks mainly at MTS and MTO only (for example: Shao and Dong, 2012 and Teimoury and Fathi, 2013). There is less research that considers all manufacturing strategies and the degree of complexity visible at AeroFirm.

Approach for complexity analysis and determining manufacturing strategy

The first stage of the research focused on identifying key complexity issues for AeroFirm. The second stage piloted the process to be used for determining appropriate manufacturing strategy.

Stage 1: Identification of complexity factors faced by AeroFirm

The first stage explored the complexity factors at AeroFirm. The aim of this stage was to really understand the supply chain complexity factors in context. The supply chain complexity factors were identified based on considering the range of factors from Christopher's (2011) identified areas and Serdarasan's (2013) classification. This stage painted a broad picture of the complexity evident at AeroFirm.

Stage 2: Manufacturing strategy decision-making process.

Olhager (2003)'s framework can be applied to focus on complexity factors more relevant specifically to determining the OPP. A mathematical model was developed to calculate the most appropriate manufacturing strategy and tested with a sample of SKUs from the European supply chain. There were factors that could not be quantified easily and/or the data was not available, these were considered at a later stage of the analysis. Four variables focused on key factors that influence the complexity at Aerofirm and reflect the three areas in Olhager's model, as shown in table 2.

Table 2 – Variables used in the calculations (mapped onto Olhager (2003)'s framework)

Quantitative Variable	**Factor based on Olhager (2003)**
1. Forecast accuracy [+/-70%] 2. Volume variability [+/- 0.25]	Market
3. Relative volume [+/- 80%]	Product
4. Supply chain depth	Production

The standard approach of Mean Absolute Percentage Error (MAPE) was used for ***forecast accuracy***, see equation 1. This makes a comparison between the forecast and actual demand figures. MAPE has been criticised as a technique when the forecast is low, however, it was effective in this case.

$$MAPE = \frac{|F-A|}{A} \qquad (1)$$

The coefficient of variation was used to model ***volume variability***, as given in equation 2 using standard formula.

$$C_v = \frac{\sigma}{\mu} \qquad (2)$$

Pareto analysis was calculated to determine the ***relative volume***. This Pareto analysis revealed the upper 80% of total demand for each plant. Any item belonging to the upper 80% was flagged. The fourth variable, ***supply chain depth,*** was more difficult to calculate, and thus supply chain managers classified each plant with upper and lower equation limit along the spectrum from make to order (MTO) to make to stock (MTS). The upper limit was closest to MTS and lower closer to MTO, hence, this gave a pseudo quantification of supply chain depth.

The overall algorithm worked by:

1. Prioritising ***relative volume*** first, any item in the top 80% of volume for the plant automatically became qualified for the upper strategies.
2. ***Volume variability*** was considered next, if this factor was less than 0.25, the item was considered to have predictable demand and therefore qualified for the upper limit strategy. If the volume variability was greater than 0.25 then demand was considered less predictable and the second highest strategy was selected.
3. Finally, ***forecast accuracy*** was the defining variable for any item not in the top 80% of volume for the plant, positioning them accordingly dependent in the lowest or second lowest strategy.

Through this algorithm, every item for each plant in the Aerofirm supply chain was provisionally categorised. This categorisation was then verified by a review from the plant and materials managers.

Findings: Supply chain complexity drivers at AeroFirm

The supply chain complexity factors for AeroFirm were evaluated to identify which ones impact AeroFirm the most. This analysis considered: static, dynamic and decision-making complexity and the origins of this (c.f. Serdarasan, 2013). It is to be noted that many of the drivers typically considered to be at the supply/demand interfaces with suppliers and customers exist internally at AeroFirm due to the high degree of vertical integration. It was evident that some of supply chain complexity factors were more significant than others for AeroFirm as the following discussion indicates.

Static supply chain complexity

AeroFirm makes a range of composite materials and also engineered products for specific customers. The product range is a major source of internal complexity, there are currently around 20,000 SKUs and this number continues to rise (c.f. range from Christopher, 2011) due to the changing of customer needs. The innovative nature of the product creates complexity due to the need for close relationships with customers at the demand interface. However, this SKU range is based on four main types of product, hence, although there are many variations, the overall product complexity is relatively low. (c.f. product from Christopher, 2011). Furthermore, as a technology leader, Aerofirm invest heavily in innovation through research and development. The demand interface is complex in terms of the customer as AeroFirm competes in 3 different marketplaces: commercial aerospace, space and defence and industrial. The industrial customers are diverse, from automotive to wind energy. These customers demand vastly different quantities and have different service level expectations (c.f. customer from Christopher, 2011). It follows that to make this range of products and serve this variety of customers that the internal supply chain requires multiple nodes (c.f. network from Christopher, 2011) through different locations, time zones and cultures (c.f. organisational from Christopher, 2011) is made up of a large variety of manufacturing and logistics processes (c.f. process from Christopher, 2011). These processes internally interact as different plants are capable of making the same products. Furthermore, there are conflicting policies across the internal supply chain, for example, different planning horizons and different stock policies. There is only one driver that can be considered as low complexity for AeroFirm and that is that they have few external suppliers to manage due to majority of single source supply(c.f. Christopher, 2011).

Dynamic supply chain complexity

There are particular complexities in the internal supply chain interfaces where there is currently a lack of process integration in terms of managing inventories. Each plant within the network is autonomous and hence, has sought to optimise their individual processes, rather than the supply network as a whole (c.f. organisational complexity from Christopher, 2011). There are several demand amplification issues generated by this, including different forecasting and inventory policies (c.f. Forrester, 1961) and order batching (c.f. Burbidge, 1984) due to different lot sizes and order frequencies across the internal network (c.f. information complexity from Christopher, 2011). Furthermore, there are many parallel interactions, which Wilding (1998) defines as "interactions that occur between different channels of the same tier in a supply network." (pp. 604). There are internal customers who could be served by more than one internal supplier and hence, there are shifts and parallel interactions that impact the processes at the same tier (in this case the "tier" being internal, rather than external). There are two main internal sources of complexities also, firstly, although there is control of processes at each plant, there is less control at an internal network level, hence, two plants making the same SKU may be operating differently (c.f. organisational complexity from Christopher, 2011). Forecast accuracy is another source of complexity at Aerofirm, as it relies heavily on stability of customer supply chain as well as complex market trends. (c.f. information complexity from Christopher, 2011).

Decision-making supply chain complexity

The organisation structure currently promotes autonomy at the different plants, which means sometimes a decision is taken that benefits one plant, but is sub-optimal for the supply network. For example, different policies in each plant can lead to a false handling of demand and result in expedited air shipment due to the conflict in approaches. The IT systems operate at a plant by plant level and this can distort demand (c.f. information complexity from Christopher, 2011), however, Aerofirm is investing in new infrastructure to enable planning across the network as both business process and IT systems are being developed to support integrated network planning.. Aerofirm has to remain vigilant in changes in the environment, including safety legislation, compliance issues and other factors that can be uncertain and uncontrollable.

The discussion of supply chain complexity drivers has been summarised in table 3 based on Serdarasan's (2013) classification.

Table 3 – Summary of supply chain complexity drivers at Aerofirm based on Serdarasan (2013)

Type	**Internal origin**	**Supply/demand interface origin**	**External origin**
Static	• Extensive product range: over 20,000 SKUs of composite materials and engineered products. • Range expands due to customisation. • Vast range of different processes and large number of assets across 18 locations.	• Product is innovative and continually developing. External network: • High complexity in terms of customers as serving many markets: commercial aerospace, space and defence and the diverse industrial applications. • Vertically integrated – few external suppliers. Internal network: • Process interactions with internal customer/suppliers • Conflicting policies in the internal supply chain	• Different and changing needs of customers. • Changing resource requirements • Aerofirm are a technology leader.
Dynamic	• Lack of control over processes at a network level. • Forecast accuracy is an issue.	Internal network: • Plants are autonomous and hence, process synchronization could be better. • Demand amplification from forecasting and	• Innovation is key, hence, focus on technology development. • Market uncertainties – relatively low in the wide view due to long term contracts.

		inventory policies and order batching. • Parallel interactions	
Decision-making	• 18 autonomous plants • Decision making process varies and some decisions are sub-optimal for the supply chain as a whole. • IT systems are disparate and varied.	Internal network: • There are differing/conflicting decisions and actions currently causing inefficiencies. • Non-synchronized decision making is evident. • Compatibility of systems across the network is currently being worked on.	• On-going changes in the regulation and compliance environment. • Uncertainty of the unknown/ uncontrollable factors.

Findings: Manufacturing strategy decision-making process

The complexities in terms of the market and customer, the product range and production/supply chain depth would indicate that all the different manufacturing strategies would be required. The particularities of the supply chain meant that two variants of make-to-stock were used to distinguish between aggregate stock of generic products (repeaters) and customer forecasted stock. The aggregate stock that will be consumed is scheduled to make efficient use production campaigns and is hence "make-to-stock". The customer-focused stock were classified as make-to-forecast (MTF), where production is scheduled according to customer forecast and efficiency of production campaign. The calculations were conducted for the eight European plants as explained in the earlier approach section. These calculations revealed the full range of manufacturing strategies were needed to meet customers' needs.

The next important stage was to the verification by materials and plants managers of the manufacturing strategy determined by the calculations. They considered the drivers that could not easily be quantified shown in table 4, and this led to the re-categorization of some of the SKUs. The plant and materials managers' verification and review was essential to ensure correct classification. An additional benefit to this involvement of plant and materials management was that they became more involved in the project and thus, this would aid the transition over to the aligned process.

Table 4 – Additional factors considered (mapped onto Olhager (2003)'s framework)

Additional factors	**Factor based on Olhager (2003)**
1. Shelf life 2. Change over time and waste 3. Materials (common – exotic)	Product
4. Production throughput time 5. Quality performance 6. Line capacity	Production

The final categorization showed the full range of manufacturing strategies were required in order to serve the customers effectively in the European plants. Make-to-forecast and assemble-to-order were the dominant strategies making up 51% and 41% of the SKUs respectively as shown in table 5. This echoes the previous analysis that revealed the complexity of the customer needs and the network. All plants had at least 2 different strategies as shown in table 5, therefore, they would need to be flexible to change between the strategies as relevant for the SKUs they manufacture. One plant was faced with all manufacturing strategies, hence, the complexity of that plant is significant.

Table 5 – Summary of manufacturing strategy analysis

	Make-to-order	**Assemble-to-order**	**Make-to-forecast** (schedule based on customer forecast and production campaign efficiency)	**Make-to-stock** (schedule based on production campaign efficiency)
Plant 1	✓	✓	✓	✓
Plant 2	×	✓	✓	×
Plant 3	✓	✓	✓	×
Plant 4	×	✓	✓	×
Plant 5	✓	✓	✓	×
Plant 6	×	✓	✓	×
Plant 7	✓	✓	✓	×
Plant 8	✓	✓	✓	×
Total % SKUs	**6%**	**41%**	**51%**	**2%**

Conclusion

This research demonstrates that a heavily vertically integrated firm faces a myriad of supply chain complexity drivers. Some complexity drivers would usually be seen at the customer and supplier interfaces as classified by Serdarasan (2013), however, vertical integration brings about the same drivers within an internal supply chain. Aerofirm is faced with managing a vast product range and serving many different customer with different expectations across a network of plants that operate somewhat autonomously. Therefore, the complexity factors are intense and furthermore, the current processes are somewhat disparate. There are different forecasting and inventory policies used and there could be more synchronization of planning across the network. This paper considered how to align manufacturing strategies across the network.

The research applied Olhager's (2003) work to classify factors that impact the OPP for Aerofirm. This work compliments the existing consideration of MTS versus MTO (Shao and Dong, 2012 and Teimoury and Fathi, 2013), and extends it due to the fact that Aerofirm's supply chain requires two further strategies: ATO and MTF. A calculation process for determining manufacturing strategy decision is proposed. The paper also identified the need to involve key personnel for verification. These key personnel harness their experience to consider further qualitative factors for deciding on optimal manufacturing strategies – essential in this complex environment. The approach proposed in this paper is likely to be adaptable for and applicable in other complex manufacturing settings.

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