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Impact of additive manufacturing on aircraft supply chain performance: A system dynamics approach

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Impact of additive manufacturing on aircraft supply chain performance

A system dynamics approach

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Abstract

Purpose – The purpose of this paper is to assess the impact of additive manufacturing (AM) implementation on aircraft supply chain (SC) networks. Additive and conventional manufacturing spare part inventory control systems are studied and compared, revealing insights into SC performance.

Design/methodology/approach – A leading global commercial airline's SC network data are used to model the research problem. A system dynamics simulation approach is followed, drawing out insights for managers.

Findings – A significant improvement in SC efficiency is observed through the implementation of AM, rendering it a worthwhile investment for global SCs. AM helps to balance inventory levels, and increase responsiveness while decreasing disruptions and carbon emissions in the supply networks.

Practical implications – The paper offers guidance on the adaption of AM in aircraft SCs and AM's impact on spare part inventory systems.

Originality/value – The study provides robust evidence for making critical managerial decisions on SC re-design driven by a new and disruptive technology. Next-generation SC and logistics will replace the current demand for fulfilling material products by AM machines.

Keywords Performance measurement, Simulation, Additive manufacturing, Supply chains, Aerospace industry

Paper type Research paper

1. Introduction

The additive manufacturing (AM) approach has captured the interest of both academia and industry in the last few years (Gao *et al.*, 2015; Schniederjans, 2017; Long *et al.*, 2017). It is estimated that the AM industry will reach $21 billion by 2020 (*Forbes*, 2015). AM is expected to revolutionise manufacturing enabling the reconfiguration of supply chains (SCs) towards more localised processes (Baumers *et al.*, 2016; Bogers *et al.*, 2016). AM, a digital technology, uses CAD files to create three-dimensional (3D) components with intricate geometries, by joining material layer upon layer (Gebler *et al.*, 2014). This layered manufacturing principle and the absence of tooling requirements enables the replacement of several conventional manufactured parts and sub-assemblies with a single integral part. The complexity of traditionally manufactured parts is directly interrelated with the costs associated with the production and value-adding activities such as packaging, labelling and warehousing (Lindemann *et al.*, 2012). The freedom of design AM offers facilitates the production of both highly customised and optimised products, assisting companies to adapt

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to changing trends in technology (Atzeni and Salmi, 2012). While many believe that AM adoption could provide a higher degree of SC performance compared to conventional manufacturing (CM), the extant literature lacks robust evidence. There is an evident lack of studies on implementing AM technologies and on industry characteristics especially favourable to AM (Khorram Niaki and Nonino, 2017a).

For companies that hold significant spare parts inventory, the efficient management of spare parts has severe cost implications (Syntetosa *et al.*, 2012). One such industry is the aircraft sector where, due to high quality and safety standards, preventive maintenance of aircraft is of paramount importance. The demand for the spare parts arises either when a random component failure occurs or when components are subjected to preventive maintenance during their lifespan (Regattieri *et al.*, 2005). The aircraft industry manages a large volume of high-value spare parts characterised by unpredictable and non-stationary demand (Simao and Powell, 2009). Furthermore, unique spare parts are characterised by a high risk of obsolescence and high shortage costs (Holmström and Partanen, 2014). Such unpredictable inventory demand for the spare parts destabilises the business of long-term suppliers. It is not a viable business investment for such suppliers to produce spare parts for older versions of aircraft in the current short life cycle-driven environment. Global demand for spare parts, traceability (for safety reasons) and high out-of-service (for grounded aircrafts) costs all compound the difficulties of efficient spare parts inventory management in the aircraft industry. It is estimated that for the commercial airlines over $40 billion of spare parts inventory is tied up in capital (Basten and van Houtum, 2014; Kilpi *et al.*, 2009). High stock levels of spare parts result in excess holding costs, and increased risk of obsolescence costs and cash flow impediment, while shortages lead to poor cycle service levels (CSLs), lack of reliability and, consequently, poor SC performance (Gu *et al.*, 2015). The cycles of maintenance, repair and overhaul services in aircraft spare parts SCs are significant challenges when trying to minimise costs (Huang *et al.*, 2013). Therefore, aircraft manufacturers face the challenge of providing much-needed components with high fulfilment rates at lower costs to match demand with supply (Khajavi *et al.*, 2014). Moreover, with the advent of AM technology, the OEM wants to locate their manufacturing facility of spare parts close to service units and equipment users (Holmström and Partanen, 2014). However, the implications of such a paradigm shift are not fully captured in the existing literature. Furthermore, the research on the implications of AM for SC performance, especially on the spare parts inventory management, is scarce in the literature (e.g. Liu *et al.*, 2014; Li *et al.*, 2017). This evident lack of research linking the impact of AM to SC performance and the general feasibility of AM technology for spare parts management raises two important research questions:

RQ1. How can the impact of AM on aircraft spare parts SCs be assessed?

RQ2. How can the overall performance difference between CM and AM implemented SC systems be captured?

To answer these research questions and capture the holistic and dynamic performance of the SC network, system synamics (SD) was found to be a suitable approach. SD is a mathematical modelling technique, with the ability to solve complex and dynamic problems (Forrester, 1958). The research attempts to provide a comprehensive SC performance assessment for making hard decisions related to the use of digital technology for managing spare parts in aircraft SC. The SD modelling approach offers further understanding of the AM's future capabilities through insights on inventory management mechanisms and feedback links. The SD models are developed to analyse and assess both AM and CM spare parts inventory management policies. The two implementation scenarios are assessed and compared to generate useful insights on the SC performance.

The remainder of this paper is organised as follows. Section 2 provides analysis of the two building blocks of the research, namely, AM implementation and aircraft spare parts inventory management. Section 3 presents the problem environment, research design and discussion on the data collection and analysis approach followed. Section 4 analyses the SD models and assesses the system's behaviour under the two scenarios studied. Section 5 summarises the research outcomes and presents theoretical and managerial implications along with limitations of the research.

2. Literature review

2.1 AM

AM is a process of fabricating objects directly from the virtual CAD data by adding material (such as metals, polymers or ceramics) without any need for tools or moulds unlike in the CM process (Atzeni and Salmi, 2012; Weller *et al.*, 2015). AM is also referred to as rapid prototyping and 3D printing. In the beginning, AM was mainly used for quick manufacturing of prototypes; however, with the increase in availability of AM machines (and raw material), along with their affordability, the production of finished products has multiplied (Atzeni and Salmi, 2012). AM can be classified into two different types based on the physical state of raw material being used (liquid, solid or powder-based processes) and the technical principal employed to deposit layers (ultraviolet light, thermal, laser or electron beam) (Baumers *et al.*, 2016). Despite the fact that various AM processes have been developed such as selective laser melting, selective laser sintering, electron beam melting and wire and arc AM (Joshi and Sheikh, 2015); the abovementioned processes have the ability to produce components with high density without any need for post-processing (Uriondo *et al.*, 2015). The commonly used material in the aircraft industry is Titanium and Nickel-based alloys. AM adoption is driven by the potential improvement of "buy-to-fly" ratio (Weller *et al.*, 2015), which is the weight ratio between the raw material used for a component and the weight of the component itself (Allen, 2006). This ratio is commonly used in the aerospace sector. Up to a 70 per cent potential reduction in the original weight of part has been estimated through the use of AM (Baumers *et al.*, 2016; Lindemann *et al.*, 2012). Hopkinson and Dickens (2003) and Ruffo *et al.* (2006) showed that certain parts with specific geometries could be produced economically using the AM technique. Improvement in the "buy-to-fly" ratio is not the only advantage derived from AM implementation; numerous other benefits have been identified in the environmental, operational and SC context. Some of the benefits include the freedom of design, small batch production, simplified assembly, less scrap and potential for simplified SCs (Lindemann *et al.*, 2012; Long *et al.*, 2017). Nevertheless, some limitations to AM implementation exist, such as quality issues and lack of globally accepted quality standards for the manufactured parts (Weller *et al.*, 2015). Especially from a safety point of view, AM still needs a considerable amount of research before achieving a reliable standard. The raw materials available for AM do not always match the characteristics of CM processes (Conner *et al.*, 2014). The manufacturing throughput speed is relatively low, and quality control standards have been initiated but not fully established (Weller *et al.*, 2015). Table I collates all the benefits and limitations of the AM adaptation from the academic literature. Overall, Table I proposes that the benefits of AM implementation appear to exceed the limitations.

Manufacturing industry experts claim that AM will soon overcome present technological bottlenecks, enhancing its capabilities and gradually replacing current CM techniques (Joshi and Sheikh, 2015; Weller *et al.*, 2015). AM's fast development is of paramount importance for the aircraft and automotive industries. This computer-based 3D printing technology has already achieved the production of low-weight aircraft components (Joshi and Sheikh, 2015). Boeing recently used selective laser sintering technology to produce thermoplastic spare parts for its commercial 737,747 and 777 aircraft (Weller *et al.*, 2015).

Similar examples of AM adoption can be found in organisations such as GE, Rolls-Royce, Airbus and NASA. It is believed that higher safety standards by aircraft industry and ongoing advances in the use of AM technology will help to improve the overall aircraft SC dynamics.

2.2 Aircraft spare parts inventory management

Increases in competition, growth in worldwide air traffic and opportunities for development in emerging economies is placing increased pressure on aircraft SCs concerning the availability of spare parts (MCTF, 2012). Spare part inventory exists to serve the defective or preventive maintenance planning, fulfilling the demand for parts that fail or are likely to fail (Gu *et al.*, 2015). According to Harrington (2007), commercial airlines maintain approximately $40 billion worth of spare parts for maintenance repair and overhaul (MRO) activities. The main challenge for any SC is to meet the requirements of a high service level with minimum inventory cost (Simao and Powell, 2009). Similarly, in the spare part inventory management, the challenge is to predict demand, which is highly intermittent (Regattieri *et al.*, 2005). Demand is often affected by stochastic factors such as wear behaviour, type of maintenance and failure rates (Lowas and Ciarallo, 2016). Wear behaviour usually depends on the phase of the aircraft's lifespan (initial, maturity or end of life phase) and failure rates can either be constant or dynamic (Basten and van Houtum, 2014). This unpredictability of demand creates forecasting difficulties, especially for new products for which the failure rate data are usually unavailable (Khajavi *et al.*, 2014). A majority of the aircraft companies use flying hours as the means to forecast demand for spare parts (Gu *et al.*, 2015). An additional challenge in the spare parts management is the variability of aircraft locations, as they keep moving across the globe. Consequently, the maintenance companies need to estimate the optimal stock level at various hubs (airports) in the network (Fritzsche, 2012). Another challenging task is the imperative need for the airlines to maintain both their previous generation aircrafts and newly launched models, increasing the number of stock-keeping units in after-sales inventory (Khajavi *et al.*, 2014). Many aircraft spare parts are high value, infrequently ordered and require long replenishment lead time (Basten and van Houtum, 2014). Given suppliers' reluctance to be involved in supplying older aircraft spare parts, spare parts inventory management is a critical problem for aircraft SCM and demands holistically assessed robust solutions.

3. Research methodology

To explore the impact of AM implementation on aircraft spare parts inventory management, the research conducts a thorough review of the existing literature in the context of both aircraft spare parts inventory management and AM implementation. The literature review supports identifying current inventory management problems in the aircraft SC. To study the impact of AM on SC performance, a comparative study follows an

Benefits and opportunities of AM	Limitations of AM
Flexibility in design and operation	Limited availability of software for manufacturing
No need for tools or moulds	High machine and material costs
Acceleration and simplification of product innovation	High calibration effort
Solution for scale-scope dilemma: no cost penalties for increased product variation	Inadequate quality standards: limited reproducibility of parts
Local production and reduced inventories	Pre and post-processing is often necessary
Less scrap and fewer raw material required	Property rights and warranty limitations

Table I. Opportunities and limitations of AM implementation

SD modelling approach. SD models for CM and AM implemented spare parts inventory management systems are developed and compared. The secondary data required for developing SD models were collected from the academic literature and publically available aircraft company reports as shown in Table AI.

SD is a computer-aided simulation approach for complex problem solving (Corinna Cagliano *et al.*, 2011; Ghadge *et al.*, 2013). The methodology, first developed by Forrester (1958), is widely used for solving industrial and business management problems. The approach is based on the systems thinking perspective that all system elements interact with each other through a causal relationship. When the system's key elements and the information feedback are successfully identified, they are then utilised to develop the causal loop diagrams (CLDs). A CLD consists of modules with polarity signs (+ or −), which demonstrate the positive or negative interactions between the elements. Later, stock and flow diagrams are developed. After the CLD and the stock and flow diagrams development, SD software is used to simulate the model. The simulation analysis tests the impact of varying input variables on the system's behaviour (Rabelo *et al.*, 2008). Vensim PLE©, a commercial simulation platform, is used for modelling and analysing the problem. Fundamental elements (influential factors and control variables) of both CM and AM aircraft spare parts inventory management are conceptualised and embedded into SD models through the development of CLD's and their respective stock and flow diagrams. In the end, sensitivity analysis is conducted to assess changes in the dynamic behaviour of the systems under examination.

3.1 Aircraft SC structure and logistics network description

An aircraft SC consists of numerous stakeholders operating globally attempting to meet supply with demand. Figure 1 shows the typical aircraft SC consisting of different SC stakeholders involved in the production, development and maintenance phase of an aircraft. The original equipment manufacturers (OEMs) such as Boeing or Airbus are responsible for the design, development and assembly of the large components, including testing and delivery of final product to their customers – i.e. airlines or nations (in the case of fighter aircraft). OEMs receive aircraft sub-assembly systems such as engines and landing

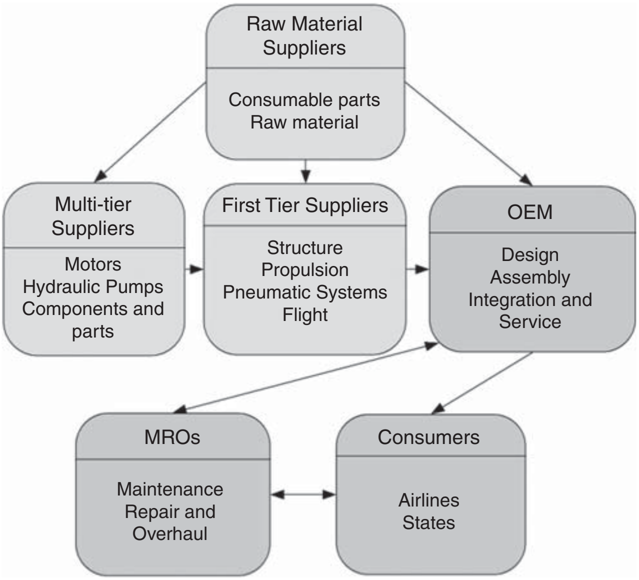

Figure 1.
The aircraft supply chain structure

gears from their first-tier suppliers, which, in turn, purchase raw materials or manufacturing products from their supplier base (Mocenco, 2015). MRO companies sign contractual agreements with either airlines or OEMs, depending on the type of network they operate in order to provide after-sales service.

Figure 2 shows that the aircraft logistics network consisting of OEM's manufacturing facilities and distribution centres (DCs) enables inventory pooling by aggregating the demand of multiple service locations (SLs). SLs are located adjacent to the installed aircraft bases (airports), where the actual maintenance takes place including restoration of repairable spare parts (Basten and van Houtum, 2014; Simao and Powell, 2009). Upon a failure, defective parts are removed and replaced by functioning ones, if they are available. The part removed can either be immediately sent to the closest repair shop or scrapped. Both DCs and SLs maintain stock to satisfy the non-stationary demand for spare parts (Liu *et al.*, 2014). If an SL experiences a stock out, the required quantities can be delivered to it from the nearest DC. Often there is the option of lateral transhipments which means that in case of a stock out, the total desirable quantities are delivered from other locations with adequate stock, even if they are owned by other airlines (Fritzsche, 2012). The demand that cannot be immediately satisfied can be backordered, meaning that purchasing orders are issued and sent to the appropriate suppliers or the OEM (Basten and van Houtum, 2014).

4. Analysis and findings

4.1 Scenario development

To study the influence of AM implementation on aircraft spare parts inventory management, two SC scenarios are presented, modelled and compared in this section.

4.1.1 CM implemented aircraft spare parts inventory management system. The fragmented logistics network depicted in Figure 3 is part of a leading global commercial airlines SC network based in North America. Different colour codes are used to distinguish between OEM (yellow), RDCs (orange) and SLs (red). In terms of research design, the region of North America is selected due to its relatively large geographical size and the availability of SC network data, which can provide realistic data examples with credible results. A focus on a specific geographic region will also avoid the complexity entailed by the examination of numerous hubs and installed bases located worldwide. The CM implemented aircraft SC network consists of an OEM, who receives purchasing orders from the MRO company. An MRO company also manages 2 regional distribution centres (RDCs) and 20 SLs, where several spare parts are kept in stock to serve different types of aircraft (Figure 3). Spare parts are shipped from the OEM's manufacturing facility to strategically located RDC's according to distance

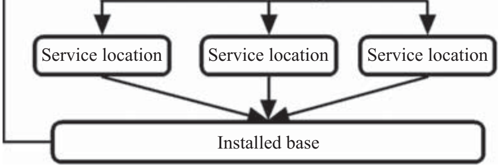

Figure 2.
Archetypical aircraft logistics network

Figure 3.
Logistics network of CM scenario (OEM→RDCs→SLs)

parameters and the proportional demand in its peripheral SLs, where the actual replacement of the defective parts takes place. The centralisation of the dispatched orders in the RDCs enables economic and efficient certification of the spare parts in terms of quality. In this scenario, all the spare parts used for maintenance are considered newly manufactured and dispatched from the OEM. The phase of spare parts in the SC network is considered to be mature/established. In the maturity phase, demand is still uncertain, but stable in comparison with the other phases, and the OEM can procure the spare parts as and when needed (Basten and van Houtum, 2014; Knofius *et al.*, 2016).

4.1.2 AM implemented aircraft spare parts inventory management system. Figure 4 shows the altered scenario when AM is implemented in the SC network. In this scenario, there is no inventory centralisation in the RDCs, as they are no longer part of the logistics network, and each SL has an AM machine installed, which can meet the demand for spare parts without the need for issuing purchase orders. The OEM is still part of the network, but is now procuring raw materials for the AM machines, instead of finished parts.

4.2 SD modelling

The SD models were developed using key elements of the respective CLD presented in Figures 5 and 6 for CM and AM implemented systems, respectively. It can be observed from both CLDs and the stock and flow diagrams (Figures 7 and 8) that the aggregated inventory level and the associated accumulated inventory holding cost constitute the main dynamic/level variables. The studied time horizon for the simulation is set as 260 weeks (5 years), assuming that during this specific time span, the OEM is capable of supplying the required spare parts, still owning the appropriate equipment and the required materials.

In the CM implemented system, the demand for the spare parts is fulfilled from the inventory available in the SLs or RDCs. Conventionally, the demand for new parts occurs at the SLs or airports and is satisfied by the inventory available on-site. If the demand exceeds the SL's available inventory, the required amount of spare parts is shipped from the closest RDC. However, in the SD models, RDCs and SLs are studied as stock-keeping units

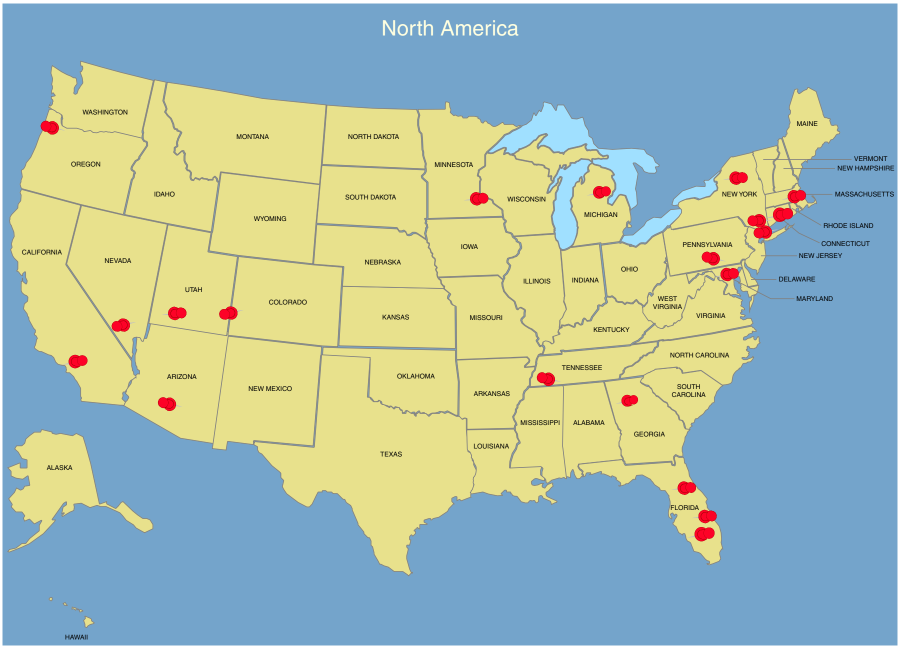

Figure 4.
Logistics network for AM scenario (SLs)

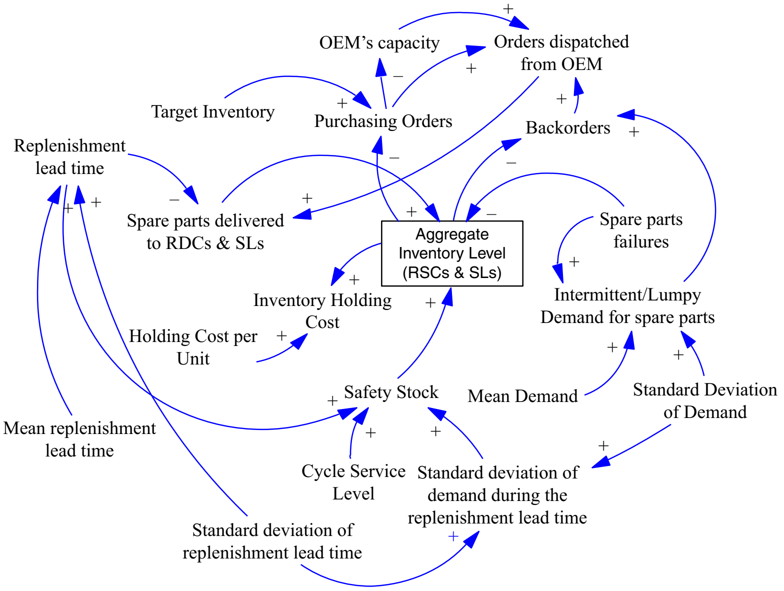

Figure 5.
Causal loop diagram for CM adopted SC system

satisfying an aggregated demand. Therefore, the aggregate inventory based on total number of RDCs and SLs is modelled. The average delay in the order replenishment is considered between the two echelons, simulating the behaviour of a real-world scenario. The next step in modelling is to allocate the inventory to the several SLs according to

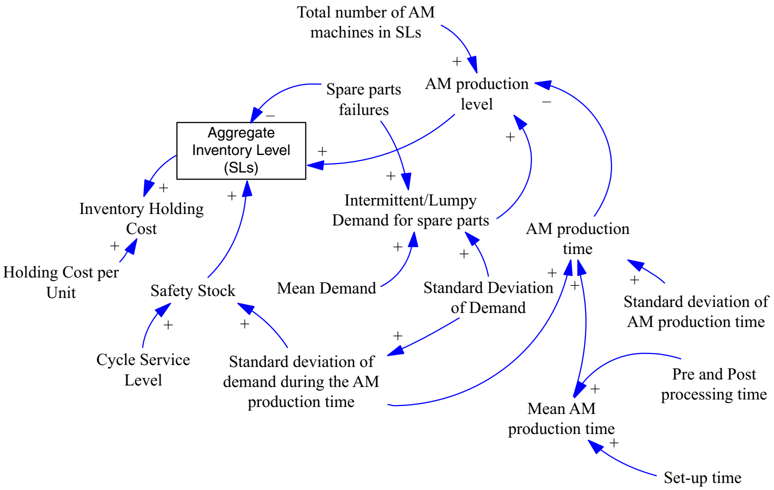

Figure 6.
Causal loop diagram for AM adopted SC system

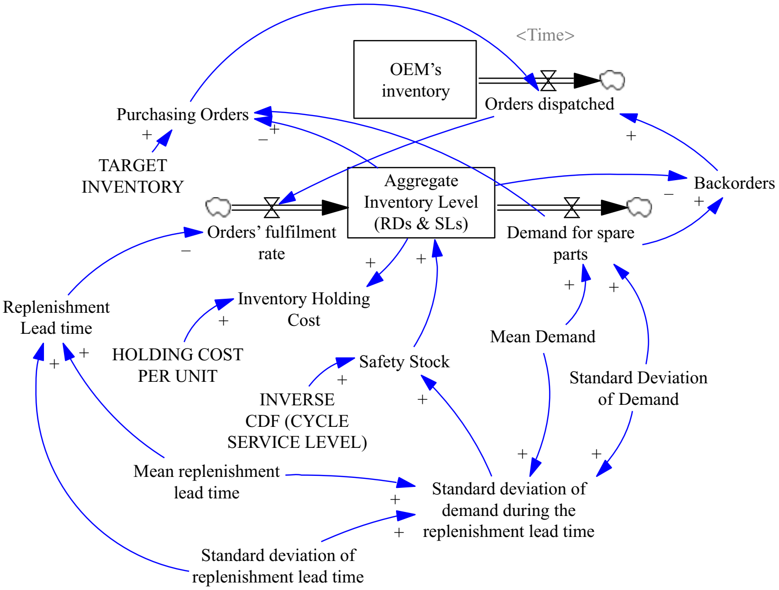

Figure 7.
Stock and flow diagram for CM adopted SC system

pre-defined demand percentages in each location. Under the AM implemented system, the demand for components of finished spare parts is satisfied by the inventory held in the SLs, where the AM machines are installed. Details regarding input variables and the equations used for the simulation run are provided in Appendix 2.

A basestock $(S-1, S)$ inventory control policy is chosen for the CM implemented system, as it is commonly used for studying inventory with stochastic demand and fixed lifetime (Kouki *et al.*, 2015). The control policy assumes that the inventory level is continuously reviewed. The purchasing order of the corresponding quantity is issued to the OEM for replenishment when inventory level falls below its initial target level.

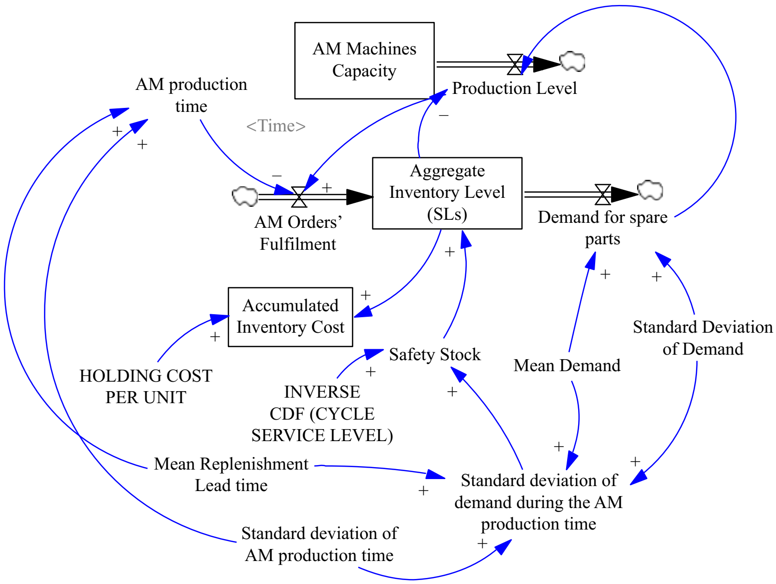

Figure 8.
Stock and flow diagram for AM adopted SC system

However, if the demand exceeds the current aggregate inventory level, backorders are raised. Ordering in batches may not be ideal, as slow-moving, expensive parts are involved, which raise the threat of becoming obsolete, if not used during the life cycle of the aircraft. Furthermore, it is assumed that the OEM has the infinite production capacity to satisfy all the purchase orders that are being issued during the given period. OEM's fulfilled orders arrive at the RDCs and SLs after a stochastic replenishment lead time that is assumed to be normally distributed with average cycle and delivery time between the three echelons (OEM→RDCs→SLs). In the case of the AM implemented system, OEM's finished spare parts inventory is considered to be zero, as parts are produced entirely on demand by the deployed AM machines at the SLs. The replenishment lead time is just the production time as the delivery lead time is zero, in the case of the AM implemented system. However, the AM production time contains the pre-processing, post-processing and set-up time (Atzeni and Salmi, 2012), and is normally distributed.

In both the scenarios, safety stock is maintained to avoid delays associated with long production times or any unexpected increase in demand. In both the scenarios, the inventory holding cost is used as an SC performance indicator. The demand for the spare parts is generated as primary data through the use of the RANDOM NORMAL function, available within the Vensim modelling platform, and is the same for both scenarios for the comparison purposes. The minimum, maximum values of demand and its mean are selected based on an approximation of the aggregated monthly demand data for the complex duct flange, a typical aircraft engine component made from Titanium (Allen, 2006) studied by Liu *et al.* (2014). This particular spare part was selected for study due to the availability of data and ease of comparison with earlier findings made by Liu *et al.* (2014).

4.3 Simulation results

In this section, the results of the simulation study are analysed and logically presented to draw a comparison between the AM and CM implemented inventory systems.

4.3.1 Aggregated inventory level. Input parameters (shown in Table AI) were provided to the simulation model. The demand distribution is kept the same in both the cases with the desired CSL set at 95 per cent. Figures 9(a) and (b) illustrate the aggregate inventory level for CM and AM implemented scenarios, respectively. A significant reduction in the aggregate inventory level was observed under the AM implemented scenario. The AM inventory at SLs constitutes about 25 per cent of the mean inventory retained at RDCs and SLs in the CM implemented aircraft spare parts management system. The primary reason for this extreme reduction in the inventory level is driven by the minimum replenishment lead time under an AM implemented system. As the spare parts are manufactured on demand near the consumption locations, the delivery time is zero as no movement of parts is involved between other SC echelons. The AM cycle time to produce the component is also less in comparison with the CM cycle time.

Also, the inventory level oscillations were observed to be smaller under the AM implemented scenario. Multiple replenishment cycles in the CM implemented scenario drives oscillations as seen in Figure 9(a). The graphical results demonstrate that AM has the potential to significantly enhance SC efficiency by significantly reducing the level of inventory in the system. This is expected to reduce the holding cost and enhances the agility of the aircraft SC network.

4.3.2 Accumulated inventory holding costs. Figure 10(a) and (b) present the accumulated inventory holding costs under the AM and CM implemented scenarios. Accumulated inventory

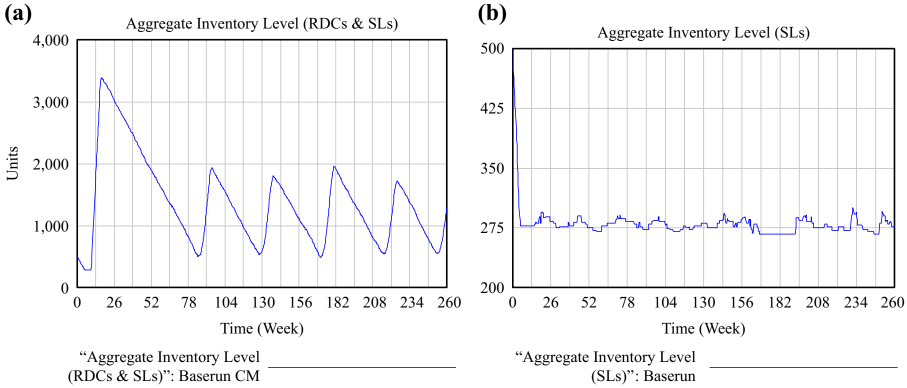

Figure 9.
Aggregate inventory level

Notes: (a) CM aggregate inventory level; (b) AM aggregate inventory level

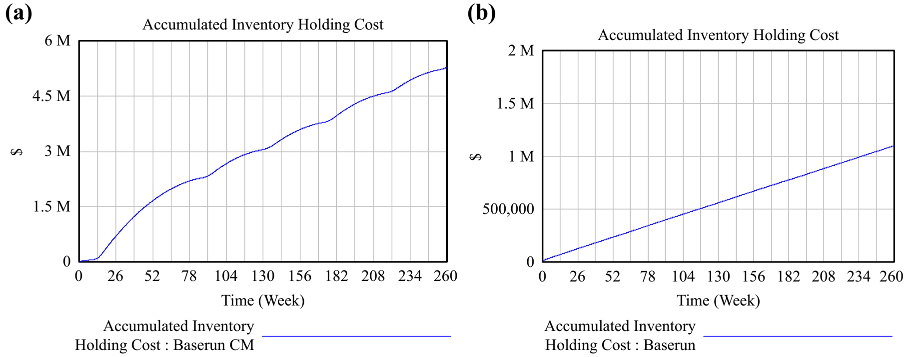

Figure 10.
Accumulated inventory cost

Notes: (a) CM accumulated inventory cost; (b) AM accumulated inventory cost holding cost for the AM implemented scenario is found to be significantly lower than the CM implemented scenario. Due to the higher inventory levels maintained in the CM accumulated scenario, the holding cost exceeds $4.5 million using a $15 inventory holding cost per spare part over a 5-year time horizon. The holding cost is found to be just over $1 million under similar conditions for the AM implemented scenario (Figure 10(b)). Obsolescence cost is a significant cost parameter and its reduction is of critical importance in order to enhance SC performance. It is evident through the graphs that the AM adoption can reduce the costs associated with obsolescence, as the spare parts are manufactured only on demand. This means there is no need for the OEM to maintain a finished spare parts inventory for a long period at their facilities and hence a further reduction in the ordering cost.

4.3.3 Sensitivity analysis. Sensitivity analysis helps to capture the system behaviour for changing input variables. Figures 11 and 12 illustrate the impact of varying service levels on aggregate inventory level under the CM and AM implemented scenarios. The abbreviations CSL1, CSL2 and CSL3 correspond to 90, 95 and 99 per cent service levels, respectively.

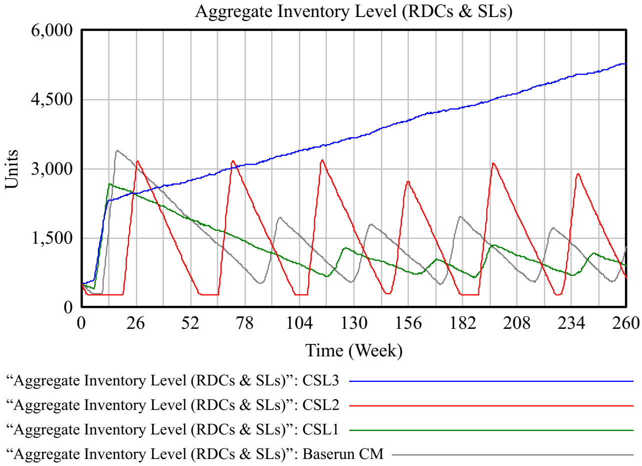

Figure 11.
The impact of varying cycle service level on the CM aggregate inventory level

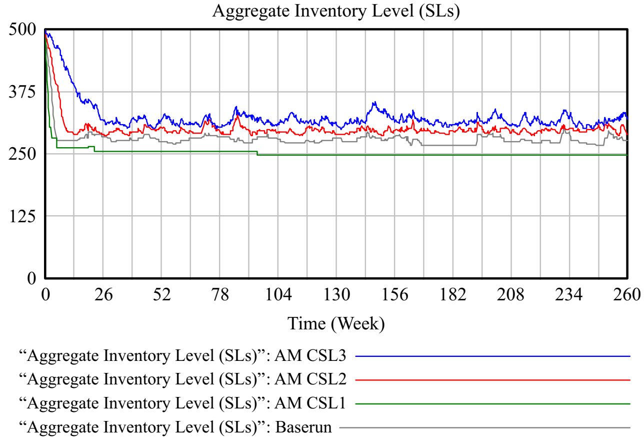

Figure 12.
The impact of varying cycle service level on the AM aggregate inventory level

It can be observed that the 99 per cent service level implies the highest maintained aggregate inventory in Figures 11 and 12. These results are consistent with the inventory management theory, which assumes that as the required service level increases, the need for inventory levels increases to ensure fast repair and downtime minimisation. Also, under the AM implemented scenario, the difference in the amount of the aggregate inventory level between the different CSL scenarios is significantly lower in comparison to the CM implemented scenario. This is due to an increased stock level requirement to meet the desired service level in the CM implemented scenario. This infers that the higher service level can be achieved in the AM implemented system without many changes in the variables of the system. This is a highly desirable outcome for the aircraft industry, as the cost of grounding an aircraft due to unavailability of parts can run into millions of dollars.

In the first simulation run (called baserun), the standard deviation of demand is assumed to be equal to the square root of the mean demand. To observe how demand parameters influence the aggregate inventory level, the sensitivity analysis is conducted by varying the standard deviation of demand from 10 to 20 per cent of the mean with a 5 per cent step increase. The other elements are kept constant, with the service level set at 95 per cent (as in the baserun). $\sigma 1$, $\sigma 2$, $\sigma 3$ denote standard deviations of 10, 15 and 20 per cent to the mean demand, respectively, for both the scenarios.

As shown in Figures 13 and 14, higher standard deviation denotes increased inventory holding in both CM and AM implemented scenarios. It was observed that with an increase in the standard deviation of demand, a higher inventory level was needed to satisfy the service level requirements. Consequently, a large amount of safety stock is mandatory to achieve the required service level under the given uncertain demand environment. The increase is significantly higher under the CM implemented scenario, especially for $\sigma 3$, where three times the aggregate inventory is required to meet demand volatility. This result is attributed to the fact that the unpredictability of demand has an impact on order interval and order quantity. In the case of AM manufactured parts, a marginal increase is attributed to increased safety stock (used to buffer against the increased demand uncertainty) as spare parts are produced on demand.

5. Discussion

5.1 Conclusion

This study examined the impact of AM implementation on aircraft spare parts inventory management. The SD modelling approach is followed to illustrate the control variables and

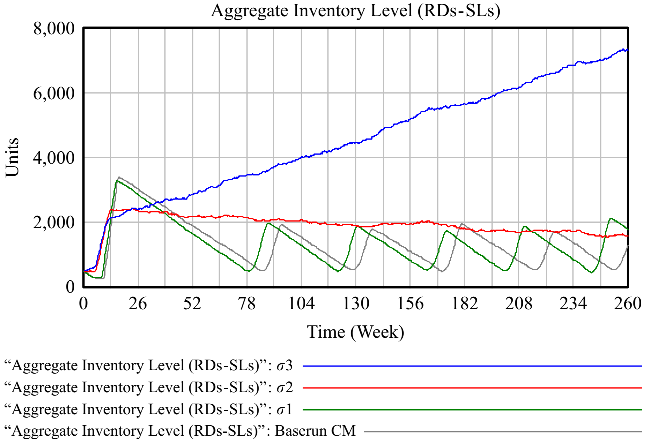

Figure 13.
Impact of varying standard deviation of demand on the CM inventory level

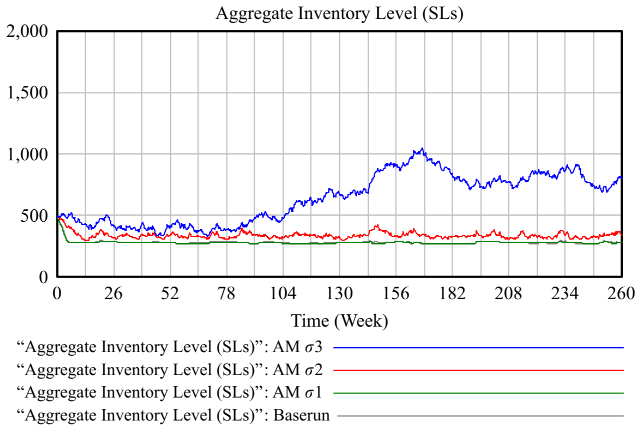

Figure 14. Impact of varying standard deviation of demand on the AM inventory level

factors influencing CM and AM implemented SCs. While attempting to answer two research questions, the study suggests that AM implementation has a strong potential to mitigate high inventory risk and achieve the required service level while eliminating downtime cost. The study also suggests that multiple network risks and external disruptions can be avoided with the adoption of the AM technology. The drastic reduction in logistics operations identified under AM implementation, and therefore an associated reduction in CO_2 emissions, means that an increase in environmental sustainability is another positive outcome of AM adoption. The aggregate inventory level under the AM scenario constitutes only 25 per cent of the mean CM inventory level. This significant reduction in inventory levels is mainly attributed to the reduced lead time and the unique SC configuration that AM implementation entails. Since SLs have AM machines installed on-site, this co-location reduces the delivery lead time of the finished spare parts to almost zero. Besides, there are no other SC echelons involved in the finished spare parts production and delivery. Hence, there is no waiting time for the order fulfilment suggesting a significant reduction in pipeline stock.

Results indicate that the elements which significantly influence the inventory level reduction are demand distribution and the desired service level. Increased demand uncertainty implies higher inventory on hold to ensure customer satisfaction. It is also observed that varying demand volumes and time intervals do not cause severe fluctuations or substantial inventory levels increases under the AM implemented scenario. Therefore, it can be established that the AM technology is of strategic importance in the aircraft SC which is characterised by uncertain demand and short life cycles. Organisations that aim to achieve high service levels usually maintain a high level of safety stock to avoid stock-outs. However, under the AM scenario, the varying service level does not have a significant impact on the inventory level. This is mainly driven by the reduced replenishment lead time (AM production time). However, under the CM implemented scenario, the longer replenishment lead time combined with the larger batch ordering to avoid stock-outs intensify the need for maintaining higher stock levels. AM implementation is not only able to reduce inventory holding costs, but also has the potential to minimise SC complexity and the costs associated with complexity. It is evident that substantial savings can be achieved over the spare parts' life cycle. It is also believed that AM implementation could support both lean and agile strategies, considering that the technology has the potential to reduce waste by minimising set up and changeover times and also energy consumption. The use of AM can evidently balance inventory levels, increase flexibility and responsiveness, while, at the same time, decreasing network complexity and likely disruptions. Overall, SC costs are mainly driven by manufacturing, inventory holding and logistics costs (Corum *et al.*, 2014). It is proven through the study that the inventory holding cost and logistics costs are significantly reduced. A moderate increase in the unit cost of (new) raw material and 3D production is expected within manufacturing costs. However, this is expected to be compensated by cost benefits achieved through remaining elements of SC costs. The research makes a further contribution to addressing and answering some of the previously unanswered questions posed in the extant literature on AM adoption in global SCs (Rogers *et al.*, 2016; Schniederjans, 2017).

5.2 Theoretical contribution and managerial implications

The paper provides evidence that the impact of AM adoption is not limited only to the design stage in today's SCs. Changes in the production decoupling point, supporting the localisation of production and offering the opportunity of manufacturing parts on demand, create substantial benefits for overall SC performance. Especially when demand for aircraft spare parts is uncertain, the research provides robust evidence that AM adoption in the aircraft SC can generate a competitive advantage. Under the given demand uncertainty for spare parts and the need for high operations service levels in aircraft SC, lead time is found to be a critical factor influencing inventory management. The research confirms that aircraft companies could improve their efficiency through AM implementation. However, this does not imply that CM will no longer be used and will be fully replaced by AM. Historically CM is used for stationary and high volume demand products; a supplementary AM capacity can be introduced for critical, low-to-medium volume spare parts that are characterised by unpredictable demand. AM's full potential for replacing the CM is still to be realised due to the high cost of investment, raw material cost and pre- and post-processing activities (Khajavi *et al.*, 2014). Hence, the potential benefits of AM are explored where production volumes are low (Hopkinson and Dickens, 2003), and coupled with unexpected surges in demand.

The SD approach to assess the holistic impact of AM implementation on aircraft spare parts inventory management is expected to fuel further quantitative and simulation-based research to assess the suitability of AM in SCM. The simulation approach followed here to replicate the real-world scenario is likely to help managers and researchers in gaining a holistic understanding of the capabilities of AM. The research contributes to research methodology in terms of the use of SD for modelling SC performance by simulating and comparing two likely scenarios for manufacturing. The research was motivated by the lack of an adequate number of quantitative studies focussing on AM implications in the SC context, as the majority of the available academic papers focussed mainly on the AM's technological or transformational aspects. Furthermore, apart from a few SC-focussed studies (e.g. Khajavi *et al.*, 2014; Liu *et al.*, 2014), the extant literature suffers from a scarcity of studies investigating AM capabilities in SC or manufacturing. Khajavi *et al.* (2014) followed a scenario analysis approach to identify potential benefits of AM for aerospace spare parts. Their scenarios are based on factors such as total operating cost and downtime cost. Similarly, Liu *et al.* (2014) followed the SCOR model to assess the impact of AM compared to CM. The research undertaken in this study goes a step further by quantitatively modelling the problem using the SD approach, thus providing robust and transparent results. Our findings complement both these studies but offer an additional contribution in assessing the total impact of AM implementation on aircraft SC performance.

The increase in SC performance that AM is seen to offer here necessarily implies organisational changes as well as horizontal collaboration within the wider SC network. Organisations would have to decide on configuring their resources (existing warehouses, DCs, production facilities and extra capacity, staff), post-AM implementation. This technology adoption-driven change has several managerial implications; for example, facility locations, supplier selection and logistics modes would need reviewing, which are some of the likely immediate implications. If AM implementation is conceived as a strategic opportunity for all SC actors, AM capabilities could continue to improve almost exponentially. In line with other technological innovations, as the number of implementers increases machine acquisition and raw material prices, the associated investment adoption costs will fall. Such a reduction of entry costs (and complexity) could, for example, attract new entrants with no background in the aircraft industry. This makes AM a disruptive technology for future SCs. Next-generation SC and logistics will replace current demand for fulfilling material products by AM machines.

5.3 Research limitations and future research

By developing SD models, the present study attempted to analyse and assess both CM and AM inventory management systems, aiming to provide insights into the potentially positive impact of AM implementation on aircraft SC performance. However, the analysis was conducted at an aggregate level due to a lack of highly specific real-life data. Rational, transparent and defensible assumptions were made to determine the parameters and values used for the formulation of the key SD elements based on a thorough understanding of aircraft SC networks, based on both a detailed review of extant literature and the research team's experience of working in the aerospace sector. Other potential methods include for example regression and relativity analysis and future research could validate the contributions made in this study following these and other appropriate quantitative methods. Another fruitful avenue for future research could be employing multiple scenarios based on who owns the inventory (OEM, MRO, airline) or AM machines, in order to identify good practices.

Although the AM technology has already found a number of applications in the medical, fashion, construction and food sectors (Mellor *et al.*, 2014; Jia *et al.*, 2016), how best to make use of AM (in this study, for example, how to reconfigure the supply network) is still some way from being realised. Therefore, it is difficult to generalise results based on the few available AM cases in specific industries, product typologies and business model contexts (Khorram Niaki and Nonino, 2017b). However, it is believed that as the number of organisations that are willing to start AM venture increases, a growing amount of case studies will be available to researchers and practitioners. Future research will surely focus on the automotive and locomotive sectors, where AM has a huge potential. The automotive industry entails lower downtime costs in comparison with the aircraft industry; thus, a different range of required service levels can be studied. A comparative study on SC performance between different dynamic sectors would provide further useful insights.

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Appendix 1

Table AI. Complex duct flange attributes and EOSINT M270 technical data

Complex duct flange attributes

Spare part name	Billet weight (kg)	Part weight (kg)	Buy-to fly-ratio	Mean CM cycle time (month)	Mean AM cycle time (month)
Complex duct flange	149.00	7.65	19:48:1	1.500	0.421

EOSINT technical data

EOSINT M270	Dimensions
Effective building volume	250 mm × 250 mm (9.85 × 9.85 × 8.5 in)
Building speed (material dependent)	2-20 mm^2/s (0.0001-0.001 in^2/s)
Laser thickness (material dependent)	20-100 µm (0.001-0.004 in)
Laser type	Yb-fibre laser
Precision Optics	F-theta-lens, high-speed scanner
Scan speed	Up to 7.0 m/s (23 ft/s)
Variable focus diameter	100-500 µm (0.004-0.02 in)
Power supply	32 A
Power consumption	Maximum 5.5 kW
Nitrogen generator	Standard
Compressed air supply	7,000 h Pa, 20 m^3/h (102 psi, 26.2 yd^3/h)

Source: EOS manufacturing solutions, see http://dmlstechnology.com/images/pdf/EOSINT_M_270.pdf (accessed 18 February 2018)

Appendix 2. VENSIM-simulation model assumptions and equations

- CM spare parts inventory management model

INITIAL TIME = 0
FINAL TIME = 260
TIME STEP = 0.25
Units for time = Weeks

Aggregate Inventory Level (RDCs & SLs) = INTEG (INTEGER (IF THEN ELSE ("Aggregate Inventory Level (RDs & SLs)" > = Demand for spare parts, Orders' fulfilment rate+ Safety Stock-Demand for spare parts, 0)))

Purchasing Orders = INTEGER (IF THEN ELSE ("Aggregate Inventory Level (RDCs-SLs)"-Demand for spare parts > = TARGET INVENTORY, 0, TARGET INVENTORY-"Aggregate Inventory Level (RDs-SLs)" +Demand for spare parts))

TARGET INVENTORY = 500

Demand for spare parts = INTEGER (RANDOM NORMAL (0, 500, Mean Demand, Standard Deviation of Demand, 0))

Mean Demand = 300

Standard Deviation of Demand = 17.32

Orders Fulfilment rate = DELAY FIXED (Orders dispatched, Replenishment Lead time, 0)

Orders dispatched = INTEGER (Purchasing orders)

OEM inventory = INTEG (INTEGER (-Orders dispatched, 1e+006))

Backorders = INTEGER (IF THEN ELSE ("Aggregate Inventory Level (RDCs-SLs)" > = Demand for spare parts, 0, Demand for spare parts-"Aggregate Inventory Level (RDCs-SLs)"))

Safety Stock = INTEGER ("INVERSE CDF (CYCLE SERVICE LEVEL)"*Standard deviation of demand during the replenishment lead time)

Standard Deviation of demand during the lead time = SQRT (Mean Replenishment Lead time*Standard Deviation of Demand^2+Mean Demand^2*Standard deviation of replenishment lead time^2)

Inverse CDF = 1.65

Accumulated Inventory Cost = INTEG ("Aggregate Inventory Level (RDs-SLs)"*Holding cost per unit, "Aggregate Inventory Level (RDs-SLs)"*Holding cost per unit)

Holding cost/unit = 15

Replenishment Lead Time = INTEGER (RANDOM NORMAL (1.42, 8, Mean Replenishment Lead time, Standard deviation of replenishment lead time, 0))

Mean Replenishment Lead Time = 6

Standard Deviation of Replenishment Lead Time = 0.5

- AM spare parts inventory management model

INITIAL TIME = 0

FINAL TIME = 260

TIME STEP = 0.25

Units for time = Weeks

AM machines capacity = INTEG (-Production Level, 105000)

Production Level = INTEGER (IF THEN ELSE ("Aggregate Inventory Level (SLs)"-Demand for spare parts > = 0, 0, Demand for spare parts-("Aggregate Inventory Level (SLs)"))

AM's order fulfilment = DELAY FIXED (Production Level, AM production time, 0)

AM production time = INTEGER (RANDOM NORMAL (1.5, 8, Mean Replenishment Lead time, Standard deviation of AM production time, 0))

Aggregate Inventory Level (SLs) = INTEG (INTEGER (IF THEN ELSE ("Aggregate Inventory Level (SLs)" > = Demand for spare parts, AM Orders' Fulfilment + Safety Stock-Demand for spare parts, 0)))

Demand for spare parts = INTEGER (RANDOM NORMAL (0, 500, Mean Demand, Standard Deviation of Demand, 0))

Mean Demand = 300

Standard Deviation of Demand = 17.32

Safety Stock = INTEGER ("INVERSE CDF (CYCLE SERVICE LEVEL)"*Standard deviation of demand during the AM production time)

Standard Deviation of demand during the AM production time = SQRT (Mean AM production Lead time*Standard Deviation of Demand^2+Mean Demand^2*Standard deviation of AM production time^2)

Inverse CDF = 1.65

Accumulated Inventory Cost = INTEG ("Aggregate Inventory Level (SLs)"*Holding cost per unit, "Aggregate Inventory Level (SLs)"*Holding cost per unit)

Holding cost/unit = 15

Mean AM production Lead time = 4

Standard deviation of AM production time = 0.2

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