Additive Manufacturing: a Decision Support System for Spare Parts Inventory Management

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Abstract
An efficient spare parts inventory management is a critical function since it affects i) the customer service in after sales operations and ii) the availability of equipment in maintenance operations for manufacturing companies. Modern spare parts' supply chains (SPSCs) exhibit unique characteristics that differentiate them from traditional supply networks of finished products. Specifically, spare parts' forecasting is rather challenging, due to their volatile demand. Moreover, the life cycle of spare parts is more extended compared to the corresponding lifetime of finished products. In response to the aforesaid challenges, Additive Manufacturing (AM) has been developed as a new manufacturing process. AM is applied mainly to rapid prototyping and provides to the management of SPSCs prospective research grounds, taking into consideration the lower manufacturing lead times and the ability to produce on demand. Nevertheless, it is difficult to detect the most suitable Stock Keeping Units (SKUs) to implement the AM processes. This paper, first reviews and analyses the existing literature on spare parts and identifies the most applicable AM technologies for spare parts production. Secondly, a Decision Support System for spare parts and AM process selection is proposed.

Keywords: supply chain management, spare parts, inventory management, additive manufacturing

Introduction

A spare part is generally defined as component that is kept in inventory and used for the repair or replacement of broken units. To that end, in order for businesses to respond to the increasing global pressures for spare parts in terms of service time and cost, they need to deploy sophisticated SPSCs. Forecasts indicate a Compound Annual Growth Rate (CAGR) of 6.93% for the Global Spare Parts Logistics Market over the period 2014-2019. The projected growth is mainly attributed to the increasing demand from China (TechNavio, 2015).

Therefore, the latter supply networks are characterized by high complexity, due to three (3) unique attributes stemming from the products' and the respective markets' demands. Firstly, this is particularly attributed to the extended life cycle of spare parts which is quite longer than that of finished products. In the automotive industry, a typical car model is usually produced for an expected lifetime of seven years, while a maintenance period of 15 years is also provisioned (Spengler and Schröter, 2003). Secondly, manufacturers tend to increase the market for spare parts' SKUs demand; hence the automotive industry firms periodically launch to the market a wide range of car models with the aim to increase the total number of required spare parts. Indicatively, a typical vehicle on average comprises of 6,000 parts, thus driving the most Chinese Original Equipment Manufacturers (OEMs) to keep an inventory of more than 30,000 SKUs (Deloitte Consulting, 2013). Thirdly, the demand for spare parts is unstable and unpredictable, driving to formless demand patterns (Bacchetti and Saccani, 2012).

Furthermore, increased customer satisfaction necessitates that a large number of SKUs is retained by an OEM in order to maintain a high fill rate. For example, Caterpillar is reported to produce more than 300 professional equipment products, and 640,000 spare parts and components with an expected lifetime of more than 40 years (Iversen, 2012). Moreover, Caterpillar distributes 18M SKUs per year in over 190 countries and provides a notable 99.7% service level within 48 hours. Additionally, the market of spare parts has become one of the most profitable sectors for a large number of industries. Specifically, while 30% of automotive OEMs' revenues come from spare parts, more than 50% of their profits originate from spare parts due to high profit margins (Bijl et al., 2000), which are 76% higher than the respective margins of the conventional finished products' market. Particularly, the profit margin in the spare parts' market is more than 40% for a third of OEMs, and more than 25% for the 70% of them (Deloitte Consulting, 2013).

In order to respond to the challenges in the spare parts' market, AM technology has been proposed to unleash opportunities for producing spare parts on demand. AM is generally defines as the "*process of joining materials to make objects from 3D model data, usually layer upon layer*" (ASTM International, 2012). Thus, AM can promote the reductions in the inventory and supply chain costs, while at the same time lead to increased service levels (Pérès and Noyes, 2006).

As opposed to traditional production methods, AM is neither recommended for mass production nor for the creation of economies of scale (Gibson et al., 2015). On the contrary, AM is a techno-economical feasible approach for producing small amount of spare parts. Spare parts demand pattern follows the 20/80 Pareto-principle. This means that 20% of demand is generated by 80% of SKUs (Huiskonen, 2001). Thus, the majority of inventory is slow moving parts and is responsible for large holding and safety costs (Liu et al., 2014). Big service providers are the most capable to implement the AM production services. Nevertheless, they retain huge databases and it is posing difficulties in the effective management of the appropriate SKUs (Sterkman, 2015). To that end, big service providers could apply robust selection criteria for determining the SKUs to be handled at every time period.

Thereafter, in this paper, we propose a list of key selection criteria for the classification of spare parts' SKUs that could be applied to most of the industrial production sectors. The rest of the paper is structured as follows. In section 2, AM advantages and challenges are provided. Following in section 3, the Decision Support System for spare parts and AM process selection is analysed. We wrap-up in section 4 with conclusions and recommendations, while future research directions are discussed.

Additive Manufacturing

Nowadays, industrial AM has become a mature technology and an increasing number of industries adopt and apply AM processes to their manufacturing applications, thus extending AM applications from mere prototyping operations. According to the literature, AM is mainly applied to the fields of prototyping, spare parts, aircraft components and medical equipment (Atzeni and Salmi, 2012; Rengier et al., 2010). Gebhardt et al. (2010) produce dental parts, especially dental crowns and bridges, using a Selective Laser Melting machine. Moreover, implants are tailored to each human body. Thus, AM proposed as an alternative manufacturing process for implants fabrication (Petrovic et al., 2011).

According to the ASTM (American Society for Testing and Materials), there are seven (7) different AM technologies: (i) VAT Photopolymerisation, (ii) Material Jetting, (iii) Material Extrusion, (iv) Powder Bed Fusion, (v) Binder Jetting, (vi) Sheet Lamination, and (vii) Directed Energy Deposition (ASTM International, 2012). For each of the aforementioned technologies, several AM processes have been developed. The most mature ones are presented in
Table 1.

Table 1: AM Technologies and compatible materials [Adapted by Gao et al. (2015)]

Technology	AM process	Abbreviation	Polymers	Metals	Ceramics
VAT Photopolymerisation	Stereolithography	SLA	X		X
Material Jetting	Polyjet / Inkjet Printing		X		
Material Extrusion	Fused deposition modelling	FDM	X	X	X
Powder Bed Fusion	Electron beam melting	EBM		X	X
	Selective laser sintering	SLS	X		
	Selective laser melting	SLM		X	X
	Direct metal laser sintering	DMLS		X	X
Binder Jetting	Indirect Inkjet Printing	3DP	X	X	X
Sheet Lamination	Laminated object manufacturing	LOM	X	X	X
Directed Energy Deposition	Laser Engineered Net Shaping	LENS		X	
	Electronic Beam Welding	EBW		X	

According to Khajani et al. (2014), AM is feasible production process for spare parts manufacturing. Its advantages relate to the offering of products and services that address consumers' requirements regarding time and cost effective delivery. In addition, reduction in inventory and logistics costs are among the first priorities for OEMs and service providers. Generally, AM optimize inventory levels since the manufactured products are produced on demand (Rommel and Fischer, 2013).

Nevertheless, AM presents significant limitations that limit their vast employability. The slow manufacturing rate and the high production cost, in case of mass production, are the two key limiting factors. Except for the slow manufacturing rate, parts can only be produced in discrete units of batches. Furthermore, an extensive knowledge of additive manufacturing processes and materials is needed to produce spare parts of high quality. Moreover, the resulting physical dimensions of a part are limited due to the high cost of the required large-scale workstations or “printers”. Finally, depending on the AM process, a post-production process is needed in order to get the finished good. Table 2 summarizes the advantages and limitations of AM.

Table 2: AM Advantages and Limitations

Advantages	Limitations
Product-on-demand.	Limited component size/small production volumes.
Small production batches are feasible and economic.	High production costs.
Possibility to quickly change design.	Requires post-processing operations
No tooling is needed significantly reducing production ramp-up time and expenses.	Knowledge of AM processes and material is needed.
Reductions of obsolete or excessive spare parts being produced at EOP and being disposed if not required.	One or a few parts can be made at a time.
Possibility to reduce waste.	Slow manufacturing rates.
Potential for simpler supply chains; shorter lead times, lower inventories.	Limited number of materials can be processed.

Spare Parts and AM Technology Selection

Spare Parts Selection Characteristics

In this section, we present a Decision Support System for selecting the most appropriate AM technology for fabricating spare parts of a specific database (Figure 1). It can be executed ether for each SKU, or for families of parts with similar characteristics. Firstly, the SKUs, which are not compatible with AM, have to be deleted. Five accept/reject criteria are applied.

The selected spare parts can be only produced from a single raw material. Thus far, a few AM processes support multi-material printing such as Material Jetting and Fused Deposition Modelling (FDM). Despite that, multi-raw material produced parts cannot be used for the repair or maintenance of a final product, but rather are used for realizing artistic sculptures and prototyping (Gao et al., 2015). Depending on the deferent types of AM processes, the main raw materials to be used in AM are polymer, metal and ceramics. From a practical point of view, the maximum dimensions of the spare parts to be produced should be selected after deciding on the investment's budget and the scale of the utilized AM printers. AM printers are available in large scales, reaching dimensions of a few meters (Gibson et al., 2015). In addition, duplicate SKUs and parts with no demand during the last 10 years have to be excluded from production scheduling and planning due to technology obsolescence and rapid changes in modern markets.

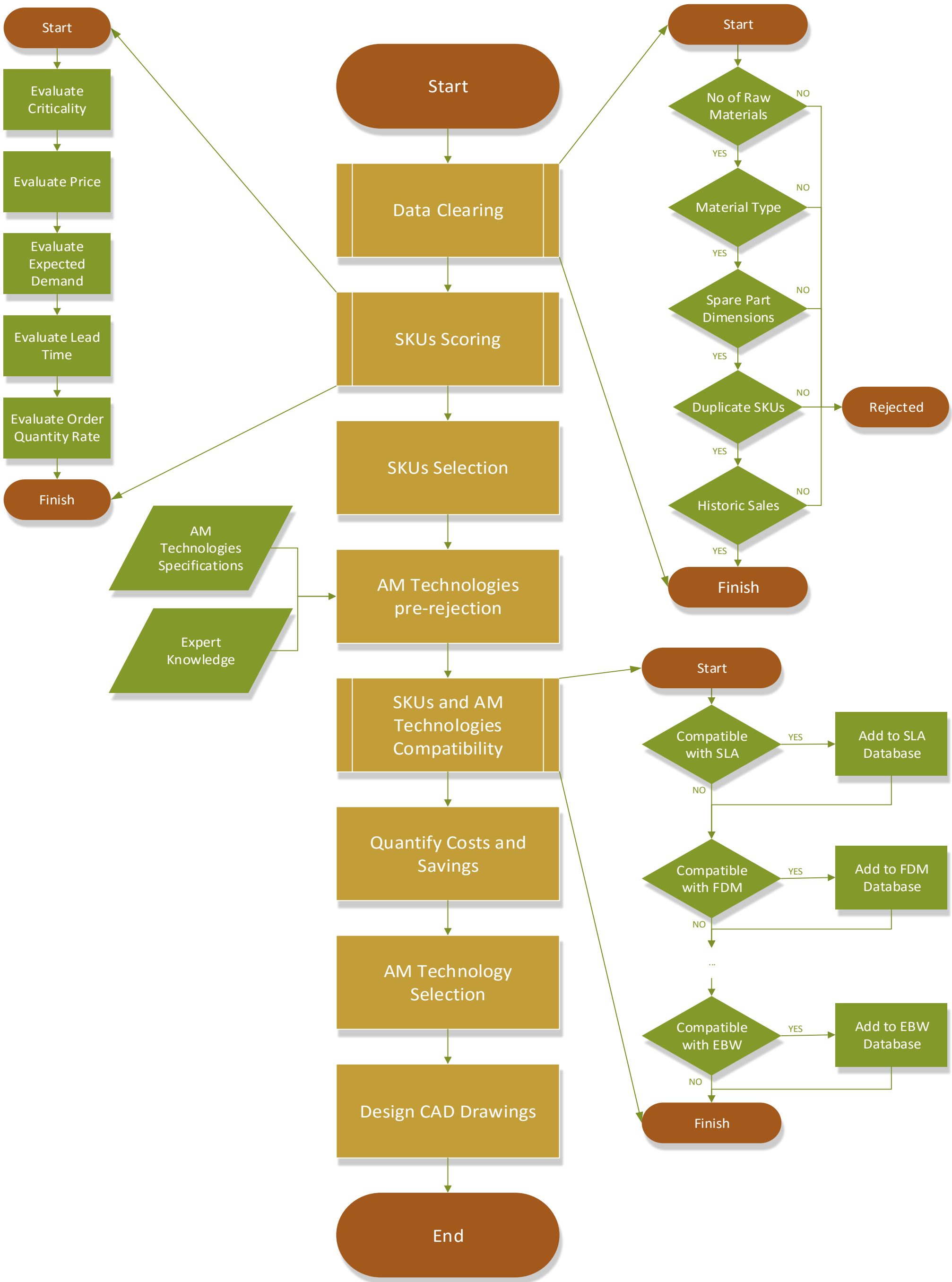

Figure 1 Decision Support System for spare parts and AM process selection

After rejected the non-applicable spare parts, the remaining are classified based on their total scores of five criteria. The first criterion is the criticality of a spare part, which has to be carefully considered. Unavailability of a critical part could result in severe consequences in the production capacity of an industry (Molenaers et al., 2012). Unexpected breakdown of a key workstation could lead to downtime of the entire production line. Downtime consequences can be categorised into two groups: downtime cost and downtime duration. Following the downtime cost can be further classified into tangible and intangible costs, and the downtime duration into scheduled and unscheduled (Prasertrungruang and Hadikusumo, 2008). Taking into account that AM printing is a time-consuming process, the time needed to print a spare part has to be lesser than the acceptable unscheduled downtime of the workstation or the production line.

Furthermore, purchasing price of a spare parts is an important factor for the AM implementation as the holding cost of the inventory is related to the production or procurement cost of the items. Consequently, AM can be more advantageous for products with high purchasing cost.

Additionally, the expected demand pattern for a specific SKU is pivotal because AM is still a more expensive manufacturing process than conventional mass production methods. This can be attributed to higher material and production capacity costs (Holmström et al., 2010). Distribution of SKUs to fast-moving and slow-moving is also necessary. Fast-moving SKUs can be produced via traditional production methods, whereas slow-moving products are recommended to be manufactured via AM.

Another key benefit of AM is the decreased lead time of the final products. Items which produced or stored in long distances often lead to low fill rate and customer satisfaction. Moreover, high lead times are responsible for increased safety stocks and inventory costs, in order to maintain the desired fill rate, highlighting the advantageous role of AM for spare parts with high lead time (Achillas et al., 2014).

Finally, a lot of suppliers require a minimum order quantity of products in order to fulfil supply contractual agreements. This is typically the case after the End-of-Production phase, when expensive molds have to be manufactured (Inderfurth and Kleber, 2013). Generally, an order quantity rate expresses the percentage of items of the minimum order quantity sold per year. A small rate determines a prolonged period preferable during which the inventory is kept on shelves.

Additive Manufacturing Technology Selection

Additive Manufacturing includes a wide range of technologies. Each technology fits best on different applications, according to its characteristics. Thus, after selecting the most applicable SKUs, the specifications of each AM technology have to be taken into account in order to reject the AM processes which are not valid for the specific spare parts. Subsequently, the compatibility between SKUs and the pre-selected AM processes have to be considered. It is evaluated by five criteria, i) Printing Materials, ii) Printing Size, iii) Accuracy, iv) Surface Quality and v) Strength. For each AM process, SKUs, which don’t exceed the AM process limits, is registered in a separate list. For each list, costs and savings of spare parts manufacturing are estimates and finally, the most suitable AM process is selected.

Conclusions & Future Research

In this paper, a combination of former research on SPSCs and AM implementation for spare parts manufacturing is presented. Based on the literature, OEMs and service providers retain large databases, containing thousands of SKUs that are difficult to manage and analyse. The practical implication of the analysis is to support the decision makers in selecting the most appropriate spare parts to be produced by the most applicable AM technology.
Further research is needed to develop conceptually the implementation of AM in a SPSC context. However, the greatest challenge is the validation of the spare parts selection scoring through empirical research. Next step is to evaluate the selection criteria over a large spare parts database.

References

Achillas, C., Aidonis, D., Iakovou, E., Thymianidis, M. and Tzetzis, D. (2014), “A methodological framework for the inclusion of modern additive manufacturing into the production portfolio of a focused factory”, *Journal of Manufacturing Systems*, pp. 1–11.

ASTM International. (2012), “Standard Terminology for Additive Manufacturing Technologies”, West Conshohocken.

Atzeni, E. and Salmi, A. (2012), “Economics of additive manufacturing for end-usable metal parts”, *International Journal of Advanced Manufacturing Technology*, Vol. 62, pp. 1147–1155.

Bacchetti, A. and Saccani, N. (2012), “Spare parts classification and demand forecasting for stock control: Investigating the gap between research and practice”, *Omega*, Elsevier, Vol. 40 No. 6, pp. 722–737.

Bijl, J., Mordret, H., Multrier, B., Nieuwhuys, S. and Pitot, N. (2000), “The evolution of the european automotive spare parts distribution market”, *Supply Chain Forum - An International Journal*, Vol. 1, pp. 70–79.

Deloitte Consulting. (2013), *Driving Aftermarket Value: Upgrade Spare Parts Supply Chain*.

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C.B., Wang, C.C.L., et al. (2015), “The status, challenges, and future of additive manufacturing in engineering”, *Computer-Aided Design*, Elsevier Ltd, Vol. 69, pp. 65–89.

Gebhardt, A., Schmidt, F.-M., Hötter, J.-S., Sokalla, W. and Sokalla, P. (2010), “Additive Manufacturing by selective laser melting the realizer desktop machine and its application for the dental industry”, *Physics Procedia*, Vol. 5, pp. 543–549.

Gibson, I., Rosen, D. and Stucker, B. (2015), *Additive Manufacturing Technologies - 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*, Springer New York, New York, NY, available at:http://doi.org/10.1007/978-1-4939-2113-3.

Holmström, J., Partanen, J., Tuomi, J. and Walter, M. (2010), “Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment”, *Journal of Manufacturing Technology Management*, Vol. 21, pp. 687–697.

Huiskonen, J. (2001), “Maintenance spare parts logistics: Special characteristics and strategic choices”, *International Journal of Production Economics*, Vol. 71 No. 1-3, pp. 125–133.

Inderfurth, K. and Kleber, R. (2013), "An Advanced Heuristic for Multiple-Option Spare Parts Procurement after End-of-Production", Vol. 22 No. 1, pp. 54–70.

Iversen, M. (2012), *Delivering Parts Availability & Inventory Performance in a Global Service Business*.

Khajavi, S.H., Partanen, J. and Holmstrom, J. (2014), "Additive manufacturing in the spare parts supply chain", *Computers in Industry*, Vol. 65, pp. 50–63.

Liu, P., Huang, S.H., Mokasdar, A., Zhou, H. and Hou, L. (2014), "The impact of additive manufacturing in the aircraft spare parts supply chain: supply chain operation reference (scor) model based analysis", *Production Planning & Control*, Vol. 25 No. 13-14, pp. 1169–1181.

Molenaers, A., Baets, H., Pintelon, L. and Waeyenbergh, G. (2012), "Criticality classification of spare parts: A case study", *International Journal of Production Economics*, Elsevier, Vol. 140 No. 2, pp. 570–578.

Pérès, F. and Noyes, D. (2006), "Envisioning e-logistics developments: Making spare parts in situ and on demand. State of the art and guidelines for future developments", *Computers in Industry*, Vol. 57 No. 6, pp. 490–503.

Petrovic, V., Gonzalez, J.V.H., Ferrando, O.J., Gordillo, J.D., Puchades, J.R.B. and Griñan, L.P. (2011), "Additive layered manufacturing: sectors of industrial application shown through case studies", *International Journal of Production Research*, Vol. 49 No. 4, pp. 1061–1079.

Prasertrungruang, T. and Hadikusumo, B.H.W. (2008), "System dynamics modelling of machine downtime for small to medium highway contractors", *Engineering, Construction and Architectural Management*, Vol. 15 No. 6, pp. 540–561.

Rengier, F., Mehndiratta, a, von Tengg-Kobligk, H., Zechmann, C.M., Unterhinninghofen, R., Kauczor, H.-U. and Giesel, F.L. (2010), "3D printing based on imaging data: review of medical applications.", *International Journal of Computer Assisted Radiology and Surgery*, Vol. 5 No. 4, pp. 335–41.

Rommel, S. and Fischer, A. (2013), "Additive Manufacturing – A Growing Possibility to Lighten the Burden of Spare Parts Supply", *IFIP Advances in Information and Communication Technology*, Vol. 411, pp. 112–123.

Spengler, T. and Schröter, M. (2003), "Strategic Management of Spare Parts in Closed-Loop Supply Chains—A System Dynamics Approach", *Interfaces*, Vol. 33 No. 6, pp. 7–17.

Sterkman, C. (2015), *Logistical Impact of Additive Manufacturing on the After-Sales Service Supply Chain of a Spare Part Provider*, University of Twente.

TechNavio. (2015), *Global Spare Parts Logistics Market 2015-2019*.