Strategic factors driving manufacturing performance of Additive Manufacturing: An empirical analysis

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Abstract

Additive Manufacturing (AM), as a leading technology contributing to the new paradigm shift Industry 4.0, is changing the way we produce and even consume. This emerging technology offers many advantages for companies to survive in the today's innovative and highly competitive business environment. Several researchers demonstrated the values of AM for supply chain, new product development, sustainability, and business opportunities. Apart from those values, the particular influence of AM on manufacturing performance needs to be carefully realized. This paper analyses the key factors driving AM manufacturing performance, and recognize the best performance areas of AM.

Keywords: Additive Manufacturing, Manufacturing performance, Theory building, Survey

Introduction

AM has brought many benefits for industry and market. Scholars are still debating on actual and potential impacts of this technology not only on operations strategy, manufacturing and logistics processes, but also on the overall business strategy investigating its actual and future sustainability.

This emerging technology is changing companies' business models, strategies and operations, bringing huge benefits for companies from the economic, social and environmental sustainability viewpoints (Niaki and Nonino, 2018). The technology is transforming the consumer experience, and the way that businesses manufacture and distribute goods (Attaran 2017). The main differences of the technology with the conventional methods rely on its tool-less and less resource-intensive nature of fabrication.

The huge advantages together with the rapid progress of technical side have attracted the attention of manufacturers in various sectors. However, most manufacturers are cautious to adopt AM as an alternative manufacturing method due to uncertain outcomes and even unknown scope of implementation. Researches (e.g., Weller et al. 2015; Khorram Niaki and Nonino 2017; and Achillas et al. 2017) argued that AM might have a different level of performance in different circumstances. For instance, Achillas et al. (2017) demonstrated that AM can compete with conventional manufacturing from the operational cost point of view only for small production volume, while regarding the lead-time, the study reveals the unconditional efficiency of AM.

Generally, it is not feasible to identify a specific factor common to all circumstances, or to generalize all the factors to a specific circumstance. Thus, this paper attempts to recognize the specific circumstances in which AM is considered as the most suitable alternative in term of manufacturing performance. These critical factors may include the operations-, organization- and product-related characteristics. To the best of our knowledge, there are a few researches in the literature (e.g., Khorram Niaki and Nonino, 2017), identifying the factors influencing the performance of AM technology. Thus, the research takes a step further in our understanding of AM management in an effort to fill the above-mentioned gaps. Consequently, this paper seeks to answer the following research questions:

- *Which are the key factors driving the AM perceived manufacturing performance?*
- *How do operational, product-related, and organizational factors influence the AM perceived manufacturing performance?*

Literature overview

The advantages of AM technologies are broadly discussed throughout the literature. These impacts are categorized based upon the scope of influence as design quality, product quality, cost and green production performance. The following paragraphs explain these performances.

Design quality performance

AM technologies enable manufacturers and product designers with some exclusive means of fabrication, which it is not technically feasible or economically justifiable using conventional manufacturing. AM mainly differs from conventional manufacturing because of its tool-less nature. It does not need moulds, fixtures, and tools that are necessary for fabrication using conventional methods. The tool-less nature of AM enables producing part of any geometry and complexity, known as *complexity-for-free*. This concept can also help designers to add the functionality of a part and to design integrated or consolidated object, which does not require further assembly operations.

Furthermore, AM offers the manufacturers a unique capability in producing parts with the lattice structure in its interior due to reducing weight, while maintaining its strength, resulting in less material usage up to 40 percent (Achillas et al., 2015). Light weighted parts are specifically beneficial for those makers producing high-value products. Moreover, AM exclusively empowers manufacturers to produce fully customized products in a sustainable manner. Although, customization is not exclusive, AM evidently enables customization without the time and cost penalties, since it offers the concept of *economy-of-one* rather than following the economies-of-scale. AM is also an effective method for accelerating creativity and innovativeness. AM assists innovation through removing conventional production constraints, offering freedom on design, ease of design modification and iteration, ease of production process, and dematerializing supply chain. Aforementioned points declare the performance of AM on improving the quality and flexibility of the design.

Product quality performance

Generally, in case of AM, product's quality is not as good as its performance in design quality. According to the several empirical studies, the technology's current drawbacks are the poor dimensional accuracy and surface roughness (e.g., Petrovic et al., 2011). AM is unable to manufacture parts that require high accuracy of dimensional measurements. Uz Zaman et al. (2017) compared dimensional tolerance ranges of conventional processes and additive processes. They argued that although AM might not be as good as traditional machining processes (such as subtractive techniques like milling), it is suitable for final product quality when compared with conventional cast-moulding processes.

However, it depends on many parameters such as geometry, material types and properties, post-processing, and the intermediate steps (Hanumaiah et al., 2007). Hopkinson et al. (2006) demonstrated that powder-based materials (i.e. Metals) have superior quality compared to liquid- or solid-based materials (i.e., plastic) that have usually a poor surface finish with grainy appearance and poor dimensional precision (Petrovic et al., 2011). Therefore, the performance of AM in terms of product's quality needs to be distinguished. We considered two components of the product quality performance including the dimensional accuracy and product's functionality and aesthetic.

Cost performance

Similar to product quality, the performance of AM on operational cost is the point of debate. There are several explicit benefits of AM for cost reduction such as labour, inventory, waste, and transportation cost as well as costs of flexibility, customization and new product development processes. However, the cost per unit of AM made parts might not be as good as those parts fabricated by conventional methods.

Generally, AM production costs consist of main components, including machine, materials, and labour (Thomas, 2016; Yeh and Chen, 2018). AM generates a shift in production cost arrangements towards a high share (45–75%) of machinery costs in the total production costs. In addition, the cost of raw material that AM processes require is relatively higher than that of conventional. The cost breakdown shows the share of each manufacturing step, as machine costs are 73% of the total costs, materials 12%, and labour 10% (Lindemann et al. 2012).

As regards workforce, since AM technologies do not need a multifunctional team for the design and running of the production line, as it is the case in most of the conventional methods, it results in a lower labour cost. Regarding inventory costs, AM allows on-demand production that can eliminate storage costs and thus reduces inventory requirements (Holmström et al., 2010). Furthermore, the ability to produce locally has profound effects on the removal of inventory costs (Tuck et al., 2007). Thus, to be consistent with the literature, we considered machine, material and labour as the components of the cost performance.

Green production performance

An aspect of sustainable manufacturing refers to the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources (Elkington, 2002). Regarding AM technologies, several researches investigated its energy consumption and other environmental impacts. The results indicate that the specific energy consumption (SEC) of AM processes is relatively higher than that of conventional (e.g., Yoon et al. 2014). However, AM may reduce energy consumption through the operations outside the manufacturing processes such as reducing transportations, reconfiguring the distributed manufacturing, reducing material waste, providing remanufacturability and design optimization. AM process parameters are important factors driving its sustainability performance. These factors include part geometry, build orientation, layer planning, and scanning speed (Paul and Anand, 2012). Thus, we considered two components of green production performance, including the energy consumption, and resource usage and pollution as other environmental impacts consistent with the literature (e.g., Le Bourhis et al., 2013).

Research framework

At above, we described the performance of AM in terms of design quality, product quality, cost and green production performance. In addition, conditional impacts of AM on these performances were explained. This section details the critical factors that are likely to drive these performances.

According to the case study analysis performed by Khorram Niaki and Nonino (2017), AM technology can reduce the cost of production, particularly for prototyping and also small volume manufacturing. AM cost performance is highly application-specific and incorporates an element of uncertainty, compounded by the lack of well-rounded AM knowledge filtering into the factors (Thomas-Seale et al. 2018). Researches indicate that the cost per unit cannot compete conventional methods due to operational cost when production volume increases (e.g., Atzeni and Salmi, 2010). Moreover, researches show that energy consumption of AM also depends on the production volume (e.g., Yoon et al., 2014). Therefore, the performance of AM is likely to be depend on production volume and scope of implementation.

Scope of implementation refers to the use of AM either in prototyping or to manufacturing of end-use products. Achillas et al. (2017) argued that conventional manufacturing (i.e. Injection moulding) can compete to AM only in large production quantities, while AM starts competing from even larger production quantities for the prototyping and tooling objectives. Weller et al. (2015) stated the benefits of AM for being employed in prototyping rather than manufacturing due to lower development costs, shortened time to market, and reduced capital intensity. Consequently, the following two hypotheses are formulated:

H1: Production volume is associated with AM perceived performance.

H2: Scope of implementation is associated with AM perceived performance.

In order to quantify the compatible production volume, we reviewed those research works conducting breakeven analysis (e.g. Hopkinson and Dickens 2001; Atzeni et al., 2010; and Atzeni and Salmi, 2012). They identified different production volumes, in which AM can compete conventional manufacturing. Their studies were case-specific in terms of different AM processes, material and the design of sample parts. Consequently, we used the findings of the literature to quantify the levels of production volume in the context of AM as follows: small-volume production [≤ 40 parts], medium [≤ 200 parts], and large [>200 Parts].

Several researches show the performance dependencies of AM technologies, based on the types of material. Atzeni and Salmi (2010; 2012) demonstrated the different performance of AM for plastic and metals in terms of costs. In terms of profitability of investment, Khorram Niaki and Nonino (2017) empirically demonstrated the less efficiency of AM for those prototypes made of plastic. According to Atzeni and Salmi, (2012) AM may offer a much better investment opportunity in comparison with conventional manufacturing, mostly for high-value parts. In addition, a buyer might be willing to pay more if finished products are customized or functionally optimized (Weller et al. 2015). Therefore, the profits of AM depend on the product’s characteristics. For instance, end-use products made of metal have greater value for a company to sell it at the higher price (Khorram Niaki and Nonino, 2017). Consequently, we formulated the following hypothesis:

H3: Type of material is associated with AM perceived performance.

Regarding the organizational factors, we first checked the consistency and correlation of a number of variables with the firm performance founded in the previous studies. In particular, we employed a control variable used by da Silveira and Sousa (2010), who investigated the firm size in regards to controlling the manufacturing performance. Several researches suggested that small businesses could not be considered the scaled-down of the larger ones and those for the large enterprises might not be suitable for the small businesses (e.g., Federici, 2009). In addition, following the study of Small and Yasin (1997), we considered the experience of the firms in regards to controlling the firm performance. They revealed that companies that had been using advanced manufacturing technologies (AMT) for more than 5 years had, on average, marginally higher performance scores than earlier adopters. In addition, several studies argued that the influence of AMT on the companies in developing countries may vary compared to developed countries (e.g., Ghani et al., 2002). AM can be considered as a strategic technology for creating value added parts and bringing back jobs for such a developed economies.

Research methodology

To address the above-mentioned research questions, an explorative survey research was conducted following the prescriptions.

Survey design and data collection

The survey questionnaire was designed based on the variables extracted from the literature. We considered four main manufacturing performance, including the design quality, product quality, cost, and green production performance all of which contain some components. Accordingly, we included in total twelve individual manufacturing performances. As for driving factors, the literatures of AM and AMT have been reviewed to extract the potential factors that are likely to drive the technology performance. In total, six sets of potential driving factors have been included such as scope of implementation, production volumes and types of material as well as country development, experience and firm size as the controlling variables.

The questionnaire after pre-testing was sent to 807 companies (AM adopters) around the world, of which, 105 companies from 23 countries participated in this survey research (about 13% of the total).

Table 1 shows the details of participants based on the included factors. The Table firstly reports the general characteristics of the firms such as the development level of the country, the firm size, its experience relating to AM technology, and positions of the respondents. These companies were founded in major developed countries (75.2%), developed countries (17.1%), and developing countries (8%). This categorization is based on the country classification of United Nation. Moreover, based on the European Commission’s recommendation in 2003, and according to the revenue and number of employees, the sample includes small and medium enterprises (SMEs) (70.5%) and large companies (29.5). These companies are also classified in terms of experience in using AM. In this way, companies with more than 5 years of experience in AM were considered as “former” (56.2%), and those with less than 5 years as “recent” (43.8%).

The respondent is composed of relevant and top level executives in the positions of chief executive officer (CEO), president, or vice president (40%), manufacturing director (23.8%), R&D, or design manager (16.2%), and other related professionals

(20%). A number of global and well-known companies participated in this survey such as General Electric; General Motors; Airbus; Ford Motor; Lamborghini; Bell & Howell; Ducati Motor Holding; Valeo; Alcoa and Festo. The survey sample includes a variety of AM application sectors and industries such as automotive, aerospace, marine, defence, electronics, medical, dental, education, architecture, art, jewellery, education and research institution, sporting goods, footwear, and food industries.

Table 1 then reports the representativeness of the sample based on the critical driving factors. The sample includes companies, which implemented AM for small-volume production (71.4%), medium (18.1%), and large (10.5%). 45.7 percent of the companies mainly implemented AM for rapid prototyping, 44.8 percent for rapid manufacturing, and 9.5 percent for other objectives. In addition, in terms of raw materials, which the company mainly used in AM, the sample includes plastic (48.6%), metal (36.2%), ceramic (5.7 %), and other types of material (9.5%) such as composite nylon carbon fiber and new metal matrix composites.

Table 1 – Case summaries

	#	%		#	%
Country Development			**Scope of Implementation**		
Major Developed	79	75.2	*Rapid Prototyping*	48	45.7
Developed	18	17.1	*Rapid Manufacturing*	47	44.8
Developing	8	7.6	*Other*	10	9.5
Firm Size			**Types of Material**		
SME	74	70.5	*Plastic*	51	48.6
Large	31	29.5	*Metal*	38	36.2
Experience			*Ceramic*	6	5.7
Former	59	56.2	*Other*	10	9.5
Recent	46	43.8	**Production Volume**		
Positions			*small*	75	71.4
CEO-President-VP	42	40	*Medium*	19	18.1
Director	25	23.8	*Large*	11	10.5
R&D-Design manager	17	16.2			
Other	21	20			

Table 2 shows the results of factor analysis and reliability analysis of the construct measures. The first factor was included four items relating to the flexibility of new product development processes, named as the design quality (flexibility) performance. The item loadings range from 0.624 to 0.843. However, according to the suggested value of reliability (0.6) by Nunnally (1978), an item (innovative and creative design) based on its effect on the Cronbach's alpha was eliminated. The second factor consists of two items relating to the quality of finished parts, named as the product quality performance. These two items have loadings greater than 0.8, and the factor reliability value exceeded the threshold. The third factor was included four items that are the components of operational costs, named as the cost reduction performance. Inventory cost was removed since the factor loading is smaller than the cut-off point, suggested by Bagozzi & Yi, (1988). The fourth factor consists of two items dealing with the environmental sustainability, named as the green production performance. No items loaded higher on subsequent factors, so these four factors (covering 73% of the variance) are used in the analysis.

The values of the Kaiser-Meyer-Olkin measures of sampling adequacy that is greater than 0.50 (Kaiser, 1974), demonstrates that the use of factor analysis is appropriate, and the extracted factors are distinct and reliable. This is also verified by the Bartlett's sphericity test, which the null hypothesis (correlation matrix is an identity matrix), is rejected (p<0.01). Tables 2 reports the results of exploratory factor analysis with the Varimax rotated component matrix.

Table 2 – Exploratory factor analysis

	Mean	St. Deviation	Loading				
Design quality (flexibility) performance			1	2	3	4	
Geometrical complex design	4.534	0.65403	0.843				
Customized product	4.3398	0.69386	0.739				
Light-weighted part	4.2524	0.71013	0.624				
Innovative and creative design	4.5146	0.55773	-				*Item removed*
Product quality performance							
Functionality and aesthetics	2.7476	1.01671		0.871			
Dimensional accuracy	3.3204	0.96216		0.854			
Cost Reduction performance							
Material cost	2.1942	0.97073			0.856		
Machin cost	2.2136	1.05394			0.853		
Labor cost	3.5728	0.99609			0.661		
Inventory Cost	3.6796	0.84266			-		*Item removed*
Green production performance							
Energy consumption	3.3204	0.89895				0.838	
Environmental impacts	3.3689	0.88551				0.811	
		***α* Cronbach**	0.72	0.75	0.64	0.62	
Kaiser-Meyer-Olkin Measure of Sampling Adequacy			0.68				
Bartlett's Test of Sphericity: Approx. Chi-Square			361.8				
		df	66				
		Sig.	0.000				

Statistical method

First, exploratory factor analysis was carried out to examine validity, and Cronbach's α for reliability analysis for each extracted construct. Convergent validity was evaluated using standardized factor loadings (Table 2). Second, a statistical method, namely Structural Equation Modelling (SEM) was chosen for two reasons. First, SEM is a technique through which multiple relationships can be simultaneously tested; some of these relationships can be mediated or moderated. Second, SEM enables testing for the existence of the mediated effects.

SEM is used where the main aim of the analysis is to test the validity of the certain relationships. The analysis usually includes a combination of confirmatory factor analysis and path analysis, where dealing with latent variables (Bollen, 1989). However, it simplifies the analysis to a path analysis where variables in the model are all manifest, in which mediation, moderation, mediated moderation or moderated mediation can all be tested (Hayes, 2017). Even though the technique has been often associated with causal inferences (Pearl, 2010), it is important to note SEM mediation analysis cannot be used to prove causality (Sobel, 2008). The main use of such techniques is to test a relationship, which is proposed based on a theoretical background, logical assumptions or research design.

Results of the analysis

Using collected data of the survey and using SEM, abovementioned hypotheses were tested. We tested the hypotheses using path analysis with control variables. The following paragraphs provide the results of the analysis. SEM is sensitive to multi-collinearity, thus we also performed a correlation analysis, among independent, dependent and control variables. The analysis suggests little collinearity among independent variables. However, moderate inter-correlation involving control variables suggest that including these variables in an analysis is important. In the analysis, dummy variables were employed as for the categorical independent variables. Moreover, the comparison of multiple models was performed using the Goodness of fit index (GFI) maximization, where the model with the highest GFI was assumed to have the best fit. Table 3 reports statistics of hypotheses testing, including the regression coefficient (β), Goodness of fit and the R square values.

Table 3 – Results of the statistical analysis

	Design Quality	Product Quality	Cost	Green
Country development	-0.0281	0.1219	**0.2061***	0.0983
Firm size	0.0697	0.039	0.00149	0.066
Experience	-0.047	-0.0262	-0.103	-0.1527
Goodness of fit index (GFI)	0.9638			
R^2	0.00559	0.0154	0.058	0.0308
Country development	-0.1648	0.1717	0.1214	0.0581
Firm Size	0.1583	0.08	-0.1076	0.061
Experience	-0.497	-0.0318	-0.0165	-0.04297
Production volume	0.0348	-0.1071	**0.3457****	**0.3027****
Scope of implementation	-0.0127	-0.0934	-0.0047	**0.2269***
Types of material	0.0505	**0.4018****	**-0.3373****	**-0.1962***
Goodness of fit index (GFI)	0.9688			
R^2	0.3761	0.1804	0.2424	0.1668

The main factors do not associate with the design quality performance; however, experience controls this dependent variable. Thus, the results show the strong effect of the experience of the companies for gaining higher design quality performance.

As regards the product quality performance, the study explores an interesting relationship. The type of material is the only factor that may drive AM perceived product quality performance. The analysis reveals that the products 3D printed with plastics are likely to have inappropriate quality, compared with metal, ceramic, or other types of materials.

Regarding the cost performance, the study explores three interesting relationships. Types of material, production volume are the factors that may drive AM perceived cost performance. Firstly, in the base model, country development controls the cost performance; however, by incorporating the main factors it does not influence the cost performance. Apart from the main factors, the results reveal that AM technologies positively and effectively influence the operational costs, especially for the companies from major developed countries. Secondly, it is surprisingly concluded that AM technologies can be considered as an efficient method for medium to large production volume (more than 40 parts in our case). Thirdly, the analysis demonstrates that AM has superior cost-efficiency for plastic materials, compared with metal, ceramic, or other types of materials.

Regarding the green production performance, the study explores three interesting relationships. All the main factors may drive the AM sustainability performance. Firstly, the analysis demonstrates that AM has superior effectiveness for those companies using AM for manufacturing of the end-use products rather than those for prototypes. Secondly, likewise the cost performance, it is concluded that AM technologies can be considered as a sustainable manufacturing method for medium to large production volumes (more than 40 parts in our case). Thirdly, similar to cost performance, the analysis demonstrates that AM has superior environmental-benefits for plastic materials, compared with metal, ceramic, or other types of materials. Consequently, regarding the hypothesis one, our study reveals that production volume may influence the manufacturing performance in terms of cost and sustainability matters. Hypothesis two is supported as scope of implementation may affect the green production performance. Finally, hypothesis three is also supported since type of material may affect product quality, cost, and green production performance.

Conclusion

A few number of research works attempted to empirically explore the impact of AM technology on manufacturing objectives and its contingent factors. Khorram Niaki and Nonino (2017) conducted the only study that considered the contingency of impacts. They identified the factors driving the impacts of AM on energy consumption, return on investment, and competitiveness using multiple case study and qualitative data. Therefore, the research contributes to expanding the literature by depicting explicit links between the implementation of this revolutionary technology and manufacturing objectives. It also provides practical insights for the adoption of AM and its impacts on the best performance area.

The study reveals the performance dependencies of AM based upon operational, product-related, and organizational factors. It concludes that the production volume plays an important role in predicting operational costs and environmental sustainability of AM. It shows that using AM as the rapid prototyping or manufacturing may have different performances in terms of environmental sustainability. It argues that types of material may influence on most of the manufacturing performances. It shows that although using plastic as raw material may have superior benefits over the other materials in terms of cost reduction and environmental sustainability, it has inferior performance in terms of product's quality. It is also concluded that gaining higher design quality depends on the maturity of firms adopting AM technology.

References

Achillas, C., Aidonis, D., Iakovou, E., Thymianidis, M., & Tzetzis, D. (2015), "A methodological framework for the inclusion of modern additive manufacturing into the production portfolio of a focused factory", *Journal of Manufacturing Systems*, Vol. 37, pp. 328-339.

Achillas, C., Tzetzis, D., & Raimondo, M. O. (2017), "Alternative production strategies based on the comparison of additive and traditional manufacturing technologies", *International Journal of Production Research*, Vol. 55 No. 12, pp. 3497-3509.

Attaran, M. (2017), "The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing", *Business Horizons*, Vol. 60 No. 5, pp. 677-688.

Atzeni, E., & Salmi, A. (2012), "Economics of additive manufacturing for end-usable metal parts", *International Journal of Advanced Manufacturing Technology*, Vol. 62 No. 9-12, pp. 1147-1155.

Atzeni, E., Iuliano, L., Minetola, P., & Salmi, A. (2010), "Redesign and cost estimation of rapid manufactured plastic parts", *Rapid Prototyping Journal*, Vol. 16 No. 5, pp. 308-317.

Bagozzi, R. P., & Yi, Y. (1988), "On the evaluation of structural equation models", *Journal of the Academy of Marketing Science*, Vol. 16 No. 1, pp. 74-94.

Bollen, K. A. (1989). *Structural equations with latent variables* John Wiley. New York.

da Silveira, G. J., & Sousa, R. S. (2010), "Paradigms of choice in manufacturing strategy: Exploring performance relationships of fit, best practices, and capability-based approaches", *International Journal of Operations & Production Management*, Vol. 30 No. 12, pp. 1219-1245.

Elkington, J. (2002). *The triple bottom line*. London: Capstone.

Federici, T. (2009), “Factors influencing ERP outcomes in SMEs: a post-introduction assessment”, *Journal of Enterprise Information Management*, Vol. 22 No. 1/2, pp. 81-98.

Ghani, K. A., Jayabalan, V., & Sugumar, M. (2002), “Impact of advanced manufacturing technology on organizational structure’, *The Journal of High Technology Management Research*, Vol. 13 No. 2, pp. 157-175.

Hayes, A. F. (2017). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach*. Guilford Publications.

Hanumaiah, N. and Ravi, B., (2007), “Rapid tooling form accuracy estimation using region elimination adaptive search based sampling technique”, *Rapid Prototyping Journal*, Vol. 13 No. 3, pp. 182-190.

Holmström, J., Partanen, J., Tuomi, J., & Walter, M. (2010), “Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment”, *Journal of Manufacturing Technology Management*, Vol. 21 No. 6, pp. 687-697.

Hopkinson, N. and Dickens, P. (2001), “Rapid prototyping for direct manufacture”, *Rapid Prototyping Journal*, Vol. 7 No. 4, pp. 197-202.

Hopkinson, N., Hague, R., & Dickens, P. (Eds.). (2006). *Rapid manufacturing: an industrial revolution for the digital age*. John Wiley & Sons.

Kaiser, H.F., (1974), “An index of factorial simplicity”, *Psychometrika*, *Vol. 39 No. 1, pp. 31-36.*

Khorram Niaki, M., & Nonino, F. (2017), “Impact of additive manufacturing on business competitiveness: a multiple case study”, *Journal of Manufacturing Technology Management*, Vol. 28, No. 1, pp. 56-74.

Le Bourhis, F., Kerbrat, O., Hascoët, J.Y. and Mognol, P., (2013), “Sustainable manufacturing: evaluation and modeling of environmental impacts in additive manufacturing”, *The International Journal of Advanced Manufacturing Technology*, Vol. 69 No. 9-12, pp. 1927-1939.

Lindemann, C., Jahnke, U., Moi, M., Koch, R. (2012), “Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing”, In *23rd Annual International Solid Freeform Fabrication Symposium–An Additive Manufacturing Conference*. Austin Texas USA 6th-8th August.

Niaki, M. K., & Nonino, F. (2018), *The Management of Additive Manufacturing: Enhancing business value*, Springer, Cham.

Nunnally, J., (1978), *Psychometric Theory*, McGraw-Hill, New York, NY.

Paul, R., Anand, S. (2012), “Process energy analysis and optimization in selective laser sintering”, *Journal of manufacturing systems*, Vol. 31 No. 4, pp. 429-437.

Pearl, J. (2010), “The foundations of causal inference”, *Sociological Methodology*, Vol. 40 No. 1, pp. 75-149.

Petrovic, V., Vicente Haro Gonzalez, J., Jordá Ferrando, O., Delgado Gordillo, J., Ramón Blasco Puchades, J., & Portolés Griñan, L. (2011), “Additive layered manufacturing: sectors of industrial application shown through case studies”, *International Journal of Production Research*, Vol. 49 No. 4, pp. 1061-1079.

Small, M. H., & Yasin, M. M. (1997), “Advanced manufacturing technology: implementation policy and performance”, *Journal of Operations Management*, Vol. 15 No. 4, pp. 349-370.

Sobel, M. E. (2008), “Identification of causal parameters in randomized studies with mediating variables”, *Journal of Educational and Behavioral Statistics*, Vol. 33 No. 2, pp. 230-251.

Thomas, D. (2016), “Costs, benefits, and adoption of additive manufacturing: a supply chain perspective”, *The International Journal of Advanced Manufacturing Technology*, Vol. 85 No. 5-8, pp. 1857-1876.

Thomas-Seale, L. E. J., Kirkman-Brown, J. C., Attallah, M. M., Espino, D. M., & Shepherd, D. E. T. (2018), “The barriers to the progression of additive manufacture: Perspectives from UK industry”, *International Journal of Production Economics*, Vol. 198, pp. 104-118.

Tuck, C., Hague, R., Burns, N. (2007), “Rapid manufacturing: impact on supply chain methodologies and practice’, *International Journal of Services and Operations Management*, Vol. 3, No. 1, pp. 1-22.

uz Zaman, U. K., Siadat, A., Rivette, M., Baqai, A. A., & Qiao, L. (2017), “Integrated product-process design to suggest appropriate manufacturing technology: a review”, *The International Journal of Advanced Manufacturing Technology*, Vol. 91 No. 1-4, pp. 1409-1430.

Weller, C., Kleer, R. and Piller, F.T., (2015), “Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited”, *International Journal of Production Economics*, Vol. 164, pp. 43-56.

Yeh, C.C. and Chen, Y.F., (2018), “Critical success factors for adoption of 3D printing”, *Technological Forecasting and Social Change*.

Yoon, H. S., Lee, J. Y., Kim, H. S., Kim, M. S., Kim, E. S., Shin, Y. J., ... & Ahn, S. H. (2014), “A comparison of energy consumption in bulk forming, subtractive, and additive processes: Review and case study”, *International Journal of Precision Engineering and Manufacturing-Green Technology*, Vol. 1 No. 3, pp. 261-279.