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Additive manufacturing best practices and its impact on supply chain performance through structural equation modelling: A case study in Ethiopian footwear industry

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Abstract. The aim of this study is to analyze the effects of additive manufacturing (AM) best practices on supply chain (SC) performance. The study developed conceptual framework with four AM best practice as independent variables and five SC performance measuring factors as dependent variables. To test the developed model and hypothesis, data's has been collected from 129 respondents from 29 footwear industries in Ethiopia. AMOS v.23 is used to test model fit with confirmatory factor analysis (CFA) ($\chi 2$/df, RMSEA, CFI, GFI, RMR, Tucker-Lewis index (TLI)). Reliability analysis was carried out to test the reliability and stability of the research questionnaires. Correlation analysis was performed to test the strength and association between dependent and independent variables. And to test the developed hypothesis structural equation modelling (SEM) or paths analysis was used. The findings of the CFA result indicated that data fit the model reasonably well. The finds of correlation analysis indicated that, AM best practices have positive, strong and significant relationship with cost, time and reliability related factors of SC performance. But it has very weak and insignificant relationship with customer related factors. In addition, the findings revelled that AM best practices have negative and insignificant relationship with supplier related factors. On the other hands, the findings of SEM confirmed that the identified four AM best practices positively and significantly improve SC performance. And this study concludes that manufacturing flexibility, material utilization, environmental control and product design optimization of AM plays a vital role in improving SC performance.

Key words: - Additive manufacturing, supply chain, best practice, footwear industry

1. Introduction

The supply chain (SC) of the existing traditional manufacturing consists of several varied elements, and it makes the system more complex. And these complex systems generate disordered environment for the organization and increase its operational load for managing diverse actors [1, 2]. As reported in [3, 4], firms are exposed to a variety of operational risks such as supply chain disruptions due to increased levels of uncertainty and unpredictability that come from complexity and increased operational load. The negative effect of operational performance comes from an increased transaction costs (e.g., production, inventory, logistics, and communication), long and unreliable lead-times, difficulty in schedule attainment and inconsistent product quality [5,6], which all are parts of or comes from supply chain complexity [7]and it affects the SC performance.

In SC management, SC performance is measured through effectiveness and efficiency [8]. To enhance effectiveness and efficiency of SC performance, a disruptive technology like AM plays a vital role [9]. According to [10], AM implementation increases customer satisfaction by promoting rapid innovation and product design modifications. Additive manufacturing has been identified as enabling major change within the supply chain [11] by

- accelerating product development times [12],
- enabling on-demand production with short lead times [13],
- affording new distribution channels [14],
- changing market structures [15], and
- Supporting a wide variety of SC structures [16].

Additive manufacturing allowed flexibility of production in case of new product development and production, and this reduces the associated time and costs [17], it allows production of difficult and nonstandard product designs [18], and this directly influences cost and time-based performance capabilities of SC (i.e. quick and inexpensive introduction of new products to the market, short manufacturing lead times, or reductions in outbound costs). In addition, AM capability towards postponement of flexibility also influences cost, reliability and customer-oriented SC performance [19] by quickly responding to changes in market demand and customer requirements and increasing order fill rate by reducing inventory-holding costs and safety stocks. And adaptation of AM technology allows sourcing flexibility and enabling suppliers to operate efficiently at different levels of production volume and varieties [20], and this intern affects supplier-oriented SC performance by enabling suppliers to quickly modify or introduce new products into the market [20]. Similarly, the study by [21] illustrated that AM flexibility leads to customer satisfaction and minimization of inventory cost, which will improve SC customer-oriented and cost performance. In addition, according to [22] flexibility influences the efficiency of the SC through reliability of deliveries (reliability performance).

According to the study in [23], AM flexibility provides the printing of products only when needed or at the time they will be utilized in production. And this transforms the production chain, it makes manufacturing on-demand, it reduces inventories and waiting times and contributing to just in time practices. The decentralized approach of AM eliminates long distances that products move within the supply chain, reducing logistics and storage costs [24]. And it has the potential to change traditional structure of supply chains and location of manufacturing [25]. According to [26], AM technologies are opening new opportunities in terms of production paradigm and manufacturing possibilities. The paper illustrated that with AM technologies manufacturing lead times will be reduced, new designs will have shorter time to market, and customer demand will be met more quickly. In addition, it explores its impact on the supply chain, and investigates its transformative potential and impact on various industry segments. Even if the best practices of AM were illustrated in the existing studies, to our knowledge no studies were conducted to illustrate its effect on supply chain performance, especially in undeveloped countries. Thus, this study aims to study the effects of AM best practices on supply chain performance in context of Ethiopian footwear industry.

2. Supply chain performance and AM best practices

According to the works reported in [27, 28], SC performance represents a construct which measures and quantifies the efficiency and effectiveness of the SC processes to strengthening the market position of the firm. To evaluate the SC efficiency and effectiveness, SC management needs to assess its performance [29]. Efficiency aims to maximize the output of the firm with minimum input by reducing costs and waste (cost-related performance), but effectiveness seeks to achieve SC optimization by increasing customer satisfaction (service-related performances) [30]. According to [9], to enhance effectiveness, companies need to strive for innovation maximization in all possible areas and seeks to be as flexible and customer oriented as possible. Implementation of AM is one of the viable investments for promoting rapid innovation and product design modifications and resulting with the increased customer satisfaction, thus improves effectiveness and it contributes to flexibility advancements [14]. Firms' SC management improved performance through the effective use of resources and capabilities, and non-financial metrics are crucial in measuring and fostering the improvement of performance of contemporary SC [31].

Nowadays, to improve the performance of SC (effectiveness and efficiency); one of the industrial 4.0called AM technology plays a vital role. Existing studies illustrated manufacturing flexibility, material utilization, product design optimization and environmental factors as few of the best practices of AM in improving SC performance. It enables major change within the SC by producing complex shapes and forms without assembly, by minimizing waste of materials without the need for custom tooling, with low manufacturing process set up, and infinitely customizable [32, 33]. In practice, this implies on-demand production with short lead times [13] and highly flexible production. This can act to significantly reduce the need for buffer inventory of finished or semi-finished goods**.** AM can simplify the SC and only raw material provider, or suppliers are needed [34]. According to the study of [35], AM technology is growing rapidly with its unique features for producing an object without requiring any special, sophisticated tools or production lines. This unique feature of AM reduces the need for logistics, time from production to sale, and environmental impact [36]. In addition, AM machines have the ability to create any shape or product without the need for any machine set-ups, which allows for levels of manufacturing flexibility. According to[37]one of the crucial areas that AM can contribute are cost reduction and simplification of organizations' supply chains. And it revealed concrete benefits of AM in reducing lead-time and number of customers.AM adoption positively influences SC performance and as a result firm performance is improved [38].AM is one of the technologies that improves efficiencies of the entire SC from the cost of distribution to assembly, resulted for high level of customization, flexibility, possibilities in logistics management and potential for production cost savings.

3. Conceptual framework work and hypothesis

3.1. Research conceptual framework

In this section, a conceptual research framework was developed based on detail literature review and in consultation with footwear industry expert. As illustrated in Figure 1, this study considered AM best practices as independent variables and it is represented by four factors as: -

(1) Manufacturing flexibility (MF),
(2) Material utilization (MU),
(3) Environmental control (EC) and
(4) Product design optimization (PDO).

And SC performance is considered as dependent variables and measured in terms of cost related factors (CRF), time related factor (TRF), customer related factor (CURF), supplier related factor (SRF) and reliability related factor (RRF).

3.2 Research hypothesis

Thus, from the developed conceptual framework and literature review the following five hypotheses were developed and tested using structural equation modelling (SEM).

- **Hypothesis 1**: AM best practices positively and significantly affects customer related factor
- **Hypothesis 2**: AM best practices positively and significantly affects supplier related factor

- **Hypothesis 3**: AM best practices positively and significantly affects cost related factor
- **Hypothesis 4**: AM best practices positively and significantly affects time related factor
- **Hypothesis 5**: AM best practices positively and significantly affects reliability related factor.

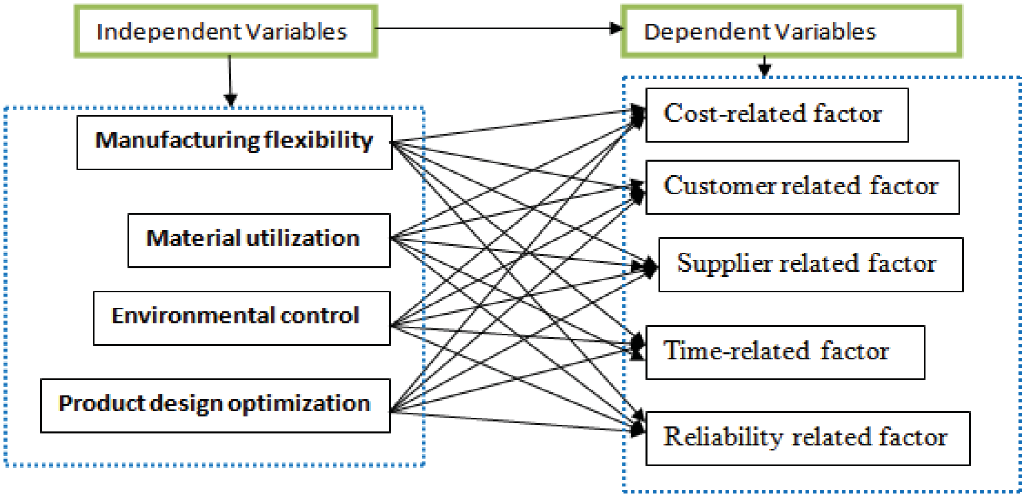

Figure 1. Conceptual framework developed from the review.

4. Methodology

In order to validate the developed research model, data for the constructs were collected using pre-coded standard questionnaire which is designed and prepared in 1 - 5 points Likert scales from 129 respondents. These scales were used to measure several constructs referring to the dependent and independent variables. The scale consists of 1=Strongly Disagree, 2=Disagree, 3=Neutral, 4=Agree and 5=strongly Agree. In data collection, 129 respondents from 29 footwear industries in Ethiopia were selected and participated in the study survey. Before the final paper was distributed, pilot test or pre-questionnaire test was conducted by distributing 25 papers. SPSS vr.20 and AMOS vr.23 were used to purify the data and analyze the confirmatory factor analysis (CFA)**.** Though several different alternatives exist for selecting the model fit statistics or to conduct CAF, this study usedχ^2/df tests, RMSEA, CFI, GFI, RMR and Tucker-Lewis index (TLI) for testing model fit by adopting and as recommended in [39]. And also, to test the path analysis for hypothesis testing, SEM was used. In addition, correlation analysis was performed to study the direction and relationship between independent and dependent variables.

5. Analysis of findings

5.1 Reliability analysis

This study conducted reliability analysis before evaluating the research model to check the reliability of the questionnaires for each construct (variable), and then separately factor analysis (FA) was carried out for individual constructs. The researchers distributed 25 papers for pilot test before the final questionnaires were distributed. The reliability analysis results are shown in Table 1, which includes the number of items before and after some items were deleted and Cronbach's alpha (α) before and after the item was deleted. As per the result of the reliability analysis as indicated in Table1, the value of Cronbach's alpha (α) dropped to 0.732 and 0.901**,** which indicated higher or satisfactory reliability of the questioners.

5.2. Confirmatory factor analysis

Based on the results listed in Table1, the factor analysis for AM best practices variables i.e. manufacturing flexibility (MF), material utilization (MU), environmental control (EC) and product design optimization (PDO) indicated that the data fits the model well. However, after removing or deleting bad factor loading item and by conducting covariance between unobserved variables, the factor loading was improved and the items were retained as shown in Table 1. The FA model fit statistics result as indicated in the table (Table 1), which indicated a good model fit because.

- the data fit the model reasonably well to all the 9 constructs;
- CFI ranges from 0.963 to 1.00;
- TLI ranges from 0.886 to 1.01 and
- GFI ranges from 0.953to 1.00.

This indicates that the model fit for all AM best practice variables are good. On the other hand, concerning the factor analysis result of SC performance, variables CRF, TRF, CURF, SRF and RRF (TLI=0.959, CFI=0.993, RMSEA=0.118, GFI= 0.989, χ^2/df= 2.774; TLI=0.948, CFI=0.974, RMSEA=0.105, GFI= 0.967, χ^2/df= 2.425; TLI=1.00, CFI=1.00, RMSEA=0.000, GFI= 1.00, χ^2/df= 0.003; TLI=0.886, CFI=0.970, RMSEA=0.039, GFI= 0.950, χ^2/df= 5.477; TLI=0.950, CFI=0.990, RMSEA=0.025, GFI= 0.988, χ^2/df= 2.077) respectively were obtained which also indicated that the model fits well

Table 1. Model fit statistics result

	χ^2/df	GFI	TLI	CFI	RMSEA	RMR	# of items	Cronbach'salpha (α)	
								Before item deleted	After item deleted
MF	3.217	0.953	0.945	0.972	0.132	0.036	5[5]	0.901	0.901
MU	1.771	0.984	0.969	0.991	0.078	0.036	5[5]	0.783	0.783
EC	0.591	0.998	1.01	1.00	0.000	0.009	5[4]	0.802	0.829
PDO	2.67	0.980	0.950	0.983	0.114	0.041	5[4]	0.788	0.816
CRF	2.774	0.989	0.959	0.993	0.118	0.018	4[4]	0.868	0.869
TRF	2.425	0.967	0.948	0.974	0.105	0.037	5[5]	0.833	0.833
CURF	0.003	1.00	1.00	1.00	0.000	0.000	6[5]	0.845	0.865
SRF	5.477	0.950	0.886	0.970	0.187	0.039	7[6]	0.879	0.891
RRF	2.077	0.988	0.950	0.990	0.092	0.025	5[4]	0.723	0.732

Figure 2 shows separate factor analysis for individual constructs. The FA result of manufacturing flexibility and material utilization variable as shown in Figure 2 (a) and (b) falls between 0.79 to 0.87 and 0.62 to 0.76 respectively after conducting covariance analysis and without removing any items from these factors. And, as shown in Figure 2 (c), FA result of product design optimization falls between o.55 to 0.89 after removing one item. The FA results for environmental related factor in Figure 2(d) shows that the factor loading falls between 0.67 and 0.9 after conducting covariance analysis and removing one lower factor loading items. On the other hand, the FA results of cost and time related factors as shown in Figure 2 (e) and (f) falls between 0.65 to 0.93 and 0.50 to 0.95 respectively without removing any items under these factors. And the factor loading of reliability related factors was improved and falls in between 0.50 to 0.76 as shown in Figure 2 (g) after removing one item. In addition, while analyzing factor loading of customer and supplier related factors, as shown in Figure 2 (h) and (i), their factor loading falls between 0.58 to 0.92 and 0.56 to 0.96 after removing one item from each factor.

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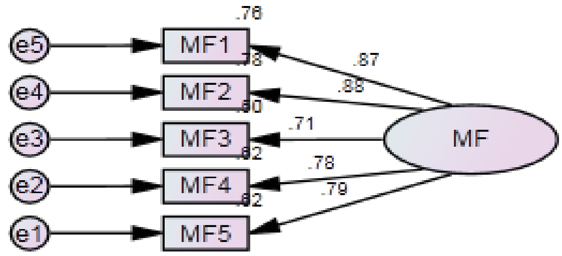
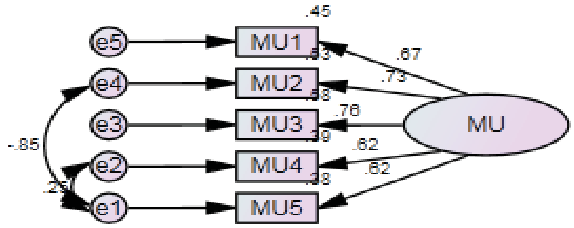
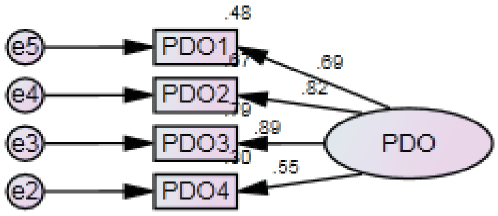


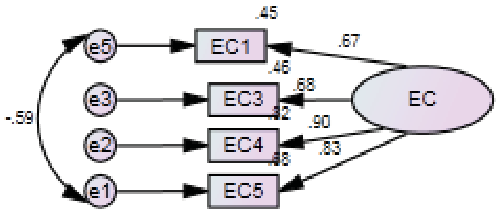
(a) manufacturing flexibility



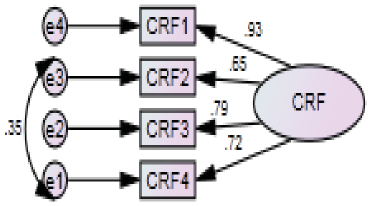
(b) material utilization



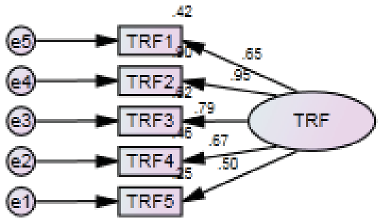
(c) product design optimization



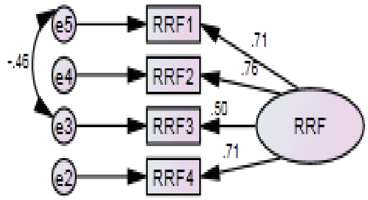
(d) environmental control factor



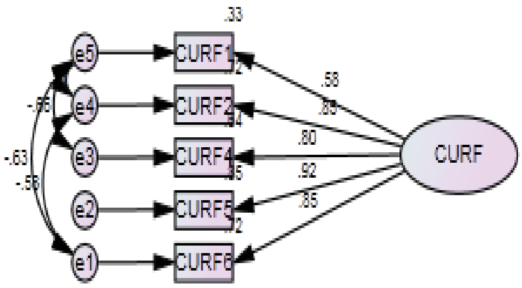
(e) Cost factor



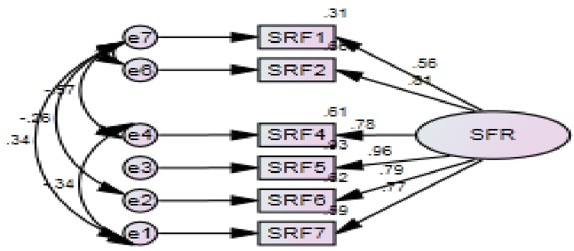
(f) Time factor



(g) Reliability factor



(h) Customer factor



(i) Supplier factor

Figure 2. Factor analysis results of independent and dependent variable

5.3 Correlation analysis

This research paper used correlation analysis to examine the strength of the relationship between AM best practices and SC performance measuring factors. The result in Table 2 shows that AM best practices have positive, strong and significant relationship with cost related factor (r = 0.539, p= 0.000), time related factor (r= 0.613, p= 0.000) and reliability related factor (r= 0.634, p= 0.000). On the other hand, AM best practices have negative and insignificant relationship on supplier's related factors (r= -0.003, p= 0.969). In addition, the result in Table 2 indicated that AM best practices have very weak and insignificant relationship with customers related factors (r= 0.01, p= 0.912). From this result, we can say that implementation of AM technologies improves supply chain performance in terms of cost, time, and reliability. From this correlation results, unexpected results were obtained showing that AM best practices have negative, very weak, and insignificant relationship with suppliers and customer related factors. These unexpected results were obtained due to smaller number of sample size.

Table 2. Correlation analysis result

		AMR	CRF	TRF	SEF	CURF	RRF
AMR	Pearson Correlation	1	.539**	.613**	-.003	.010	.634**
	Sig. (2-tailed)		.000	.000	.969	.912	.000
	N		129	129	129	129	129
CRF	Pearson Correlation		1	.011	.456**	.490**	.218*
	Sig. (2-tailed)			.900	.000	.000	.013
	N			129	129	129	129
TRF	Pearson Correlation			1	-.445**	-.460**	.534**
	Sig. (2-tailed)				.000	.000	.000
	N				129	129	129
SEF	Pearson Correlation				1	.965**	.047
	Sig. (2-tailed)					.000	.595
	N					129	129
CURF	Pearson Correlation					1	.019
	Sig. (2-tailed)						.830
	N						129
RRF	Pearson Correlation						1
	Sig. (2-tailed)						
	N						129

**Correlation is significant at the 0.01 level, *Correlation is significant at the 0.05 level (2-tailed)

5.4 Structural modelling analysis

The developed hypothesis in Section 3.2 was tested using path analysis (SEM) and the results are shown in Figure 3, in which a positive and significant effects of AM best practices on SC performance cost related factor (β= 0.54, p=0.000) is observed. Hence hypothesis 1 is accepted. Similarly, the findings of the study illustrated that AM best practices have positive and significant effects on time related factor (β = 0.61, p = 0.000) and this also supports hypothesis 2. The results of SEM analysis also confirmed that SC performance customer related factor positively and significantly affected by AM best practices (β = 0.01, p = 0.000). Hence hypothesis 3 is supported.

On the other hands, material utilization, manufacturing flexibility, product design optimization and environmental best practices of AM significantly and positively influencing reliability related factor of SC

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performance (β = 0.63, p = 0.000) and this accepted hypothesis 4. The results of the analysis in Figure 3 also illustrated that the four AM best practices positively and significantly affects supplier related factor of SC performance measuring factor (β= 0.02, p=0.000). Thus, this also supported hypothesis 5.

These hypotheses testing results confirmed that all the identified AM best practices (material utilization, manufacturing flexibility, product design optimization and environmental factor) have positive and significant impacts in improving SC performance (efficiency and effectiveness). The result illustrated and supported or in line with the findings of existing studies. Through implementation of AM process, reliability of SC performance is improved by reducing buffer inventory of finished or semi-finished goods and improves customer-oriented performance through manufacturing flexibility without the need of tooling and new machine setups. On the other hands, adaptation of AM improves SC cost related performance by delivering raw material on time and logistic related costs. It improves customer satisfaction by promoting on demand production with shorter lead time, and high flexible production. It improves effectiveness of SC by reducing time from supplier to production, from production to sales and through reduction of carbon footprint.

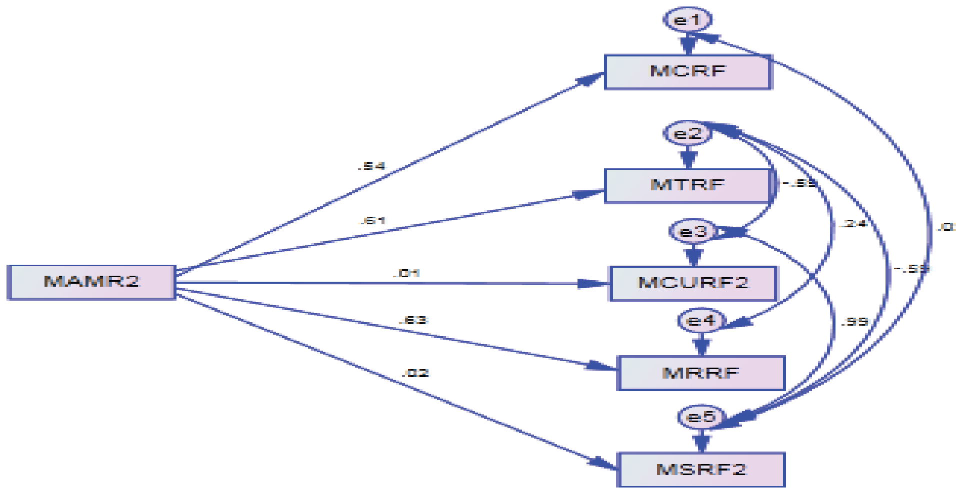

Figure 3.SEM path analyses

6. Conclusion

This study aims to analyze the effects of AM best practices on supply chain performance. The study identified four AM best practices and five SC performance measuring factors from the literature review. To test the developed conceptual framework and hypothesis, data have been collected through 1- 5 liker scale from 129 respondents from 29 footwear industries in Ethiopia. Through pilot study the reliability and validity of the questionnaires was tested. Correlation analysis was used to examine the strength of the relationship between independent factors (MF, MU, EC, and PDO) and dependent VARIABLES (CRF, TRF, CURF, SRF and RRF). And the model fits and the hypothesis were tested using confirmatory factor analysis and structural equation modelling respectively. And in conclusion the four AM best practices: - (a) manufacturing flexibility (MF), (b) material utilization (MU), (c) environmental control (EC) and (d) product design optimization will improve the performance of supply chain.

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