A Proposed Framework in Developing Sustainable Manufacturing Initiatives using Analytic Hierarchy Process (AHP)

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Abstract: This paper proposes an evaluation framework of input elements in developing sustainable manufacturing (SM) initiatives using the hierarchical structure of sustainability indicators set developed by the US National Institute of Standards and Technology (US NIST) in the context of the analytic hierarchy process (AHP). Determining priority input elements in the development process is essential to ensure that SM initiatives are responsive to the demands of sustainability at firm level. This evaluation exposes a challenge due to the multi-criteria nature of the problem and the presence of subjective criteria with limited available information on their measurement systems. The use of AHP along with the hierarchical structure of the US NIST sustainability indicators set provides a comprehensive and promising approach in identifying fundamental inputs in developing effective programs and initiatives that address sustainability. The contribution of this work lies in presenting a framework that could guide decision-makers, in a way that is simple and comprehensive, in their attempt to promote sustainability. Results and implications are reported in this work.

Keywords: Input Elements, Sustainable Manufacturing, Evaluation, Analytic Hierarchy Process, Multi-Criteria Decision-Making

1. Introduction

Increasing global issues on sustainability encourage manufacturing firms to structure their decisions relating to their products and processes beyond traditional profit-based approaches. This agenda has been the focal point of research following the seminal report published by the United Nations' World Commission on Environment and Development (UN-WCED) (Brundtland, 1987). In this regard, manufacturing industry has been a key sector in sustainability (Rosen and Kishawy, 2012; Joung et al., 2013) such that a special attention is currently attributed to sustainable manufacturing (SM) which has been defined by the U.S. Department of Commerce as "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers and are economically sound" (Joung et al., 2013). This gains interests both in theory and practice and has motivated leading developed economies (Kovac, 2012).

The development and implementation of SM approaches are conventionally gauged using sustainability indicators that measure and monitor performance of firms (Ragas et al., 1995). The underlying concept is to address sustainability in three widely accepted dimensions, i.e. environmental, economic and social dimensions, popularly known as the triple-bottom line (Elkington, 1997). A number of indicator sets have been published by renowned institutions, international agencies and bodies, universities, government and industries. A review of these indicator sets is carried out in several works, e.g. Joung et al. (2013), Singh et al. (2012), Böhringer and Jochem (2007), Mayer (2008). Most often, a hybrid of these sets have been used to assess and evaluate sustainability in different domains. Chen et al. (2012) used SM indicators for factory planning process. Jawahir et al. (2007), de Silva et al. (2009) and Gupta et al. (2011) used product sustainability indicators at different stages of the product life cycle. Currently, the most critical and comprehensive framework of SM indicators was carried out by Joung et al. (2013) in which results were eventually adopted by the US National Institute of Standards and Technology (US NIST). The proposed framework of Joung et al. (2013) comprises a careful integration of 11 internationally-accepted sustainability indicator sets published by various institutions. The strength of the framework lies in its hierarchical structure such that relationships among elements of the framework can be easily assessed and as one goes down in a hierarchy, the level of information details gradually increases.

Apparently, developing SM initiatives can be suitably considered as a multi-criteria decision problem due to a number of criteria that must be brought into context when assessing relevant elements according to its priority in addressing sustainability. This becomes more complex as an effect of the presence of subjective criteria with available limited information on its measurement systems. Various methods have been developed and applied in modeling, planning and selection of SM strategies. These include mathematical programming techniques (Chaabane et al., 2012; Kravanja and Cucek, 2013), simulation methods (Jain and Kibira, 2010) and multi-criteria decision-making methods (MCDM) (Gupta et al., 2011, Baskaran et al., 2012; Vinodh and Jeya Girubha, 2012). Note that this list is not intended to be comprehensive. One important consideration in selection problems is the ability of the method to address assessment involving value judgments, assumption and scenarios (Heijungs et al., 2010) which are characteristics of MCDM methods (Herva and Roca, 2013). A number of these MCDM methods were developed and were used to address selection problems which include the analytic hierarchy process (de Brucker et al., 2013), analytic network process (Tseng et al., 2009a), fuzzy set theory (Tseng et al., 2009b), preference ranking organization method for enrichment evaluation (PROMETHEE) (Vinodh and Jeya Girubha, 2012), grey theory (Baskaran et al., 2012) and decision-making trial and evaluation laboratory (DEMATEL) (Tseng et al., 2012). A plausible review of MCDM techniques can be found in Cho (2003).

Herva and Roca (2013) indicated that AHP/ANP and outranking methods are commonly used in industry-related applications. Because of its logical and simple structure in handling comprehensive evaluation of multi-tier decision problems, AHP is used in this paper in the selection of input elements in developing SM initiatives. AHP is a theory of measurement developed by Saaty (1980). In AHP, a decision problem is logically expressed as a hierarchy of decision components and elements and their priorities are derived from judgment elicitation through pair wise comparisons (Saaty, 2008). Numerous applications of AHP in sustainability assessment can be found in literature, e.g. Krajnc and Glavic (2005); Chatzimouratidis and Pilavachi (2009); Gupta et al. (2011); Garbie (2011); Chiacchio (2011); de Brucker et al. (2013). A critical review of AHP and its applications were carried out by Vaidya and Kumar (2006) and Subramanian and Ramanathan (2012).

Although sustainability assessments are popular in current literature, evaluation of elements from a comprehensive framework that should be inputs in developing SM initiatives is scarce, see Chen et al. (2012), Jawahir et al. (2007), de Silva et al. (2009) and Gupta et al. (2011) for related works. This paper attempts to propose a selection process of input elements in developing SM initiatives which has an evaluation framework based from US NIST and a prioritization process using AHP. This work is of particular importance in SM research as it provides plausible insights for managers and decision-makers at firm level on developing SM initiatives. This aids in decision-making problems that comprise both tangible and intangible components having multi-dimensional scales. This paper is organized as follows. Section 2 provides the general methodology of this study. Section 3 shows the results and discussion of the selection process using AHP and relevance of the results in sustainability research. Section 4 concludes the study with a future possible work.

2. Proposed Method

2.1 Analytic Hierarchy Process

AHP is a powerful tool in multi-criteria decision analysis (MCDA) especially in hierarchical decision-making. AHP decomposes a decision problem into components of different levels. Decomposition is significant in decision analysis as it provides a depth, comprehensive and organized decision-making process. Decision-makers elicit pairwise comparisons, based from their value judgments, of the elements in the same level with respect to an element in higher immediate level. Generally, the procedure of the AHP can be described as follows:

2.1.1 Structuring the Decision Problem

In AHP, decision problems are structured hierarchically in a top-down approach (Saaty, 2007). Oftentimes in many selection problems, there is an explicit definition and representation of goal, criteria and alternatives components. In various cases, criteria component is described in more than two levels so that further details of criteria are explicitly presented in the problem structure. Choosing components and alternatives is usually carried out either through a critical review of literature with regard to the facets of the decision problem or through an expert or group of experts who have sufficient knowledge and experience of the problem under consideration. Decision components and elements are usually a combination of both objective and subjective ones, with measurements in different and multiple dimensions.

2.1.2 Eliciting Judgment in Pair Wise Comparisons

Through experts' knowledge, pair wise comparisons of elements in the same level with respect to an element in the immediate higher level are carried out in the AHP. The generic question in making pairwise comparisons goes like this: "Given a parent element and given a pair of elements, how much more does a given member of the pair dominate other member of the pair with respect to a parent element?" (Promentilla et al., 2006). To achieve a uni-dimensional scaling property of the comparisons, Saaty (1980) established the famous Saaty fundamental 9-point scale as shown in Table 1. In pairwise comparisons, a reciprocal characteristic exists. For instance comparing a_1 and a_3 with a rating of 3 should imply that comparing a_3 and a_1 must be rated 1/3 which is the reciprocal of 3. The principal priority vector or weights (w) are obtained from the pairwise comparison matrix (A) by solving an eigenvalue problem in the following relation:

$$Aw = \lambda_{max} w \tag{1}$$

where λ_{max} is the maximum eigenvalue of the positive reciprocal square matrix (A). The approach also provides a way to measure the consistency of judgments in the pairwise comparison matrix. When decision-making in the pairwise comparisons matrix is consistent $\lambda_{max} = n$; otherwise, $\lambda_{max} > n$ where n is the number of elements being compared. The Consistency Index (CI), as a measure of degree of consistency, was calculated using the formula

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

The consistency ratio (CR) is computed as

$$CR = \frac{CI}{RI} \tag{3}$$

where RI is the mean random consistency index, see Alonso and Lamata (2006) for Tables of RI. $C.R. \leq 0.10$ is an acceptable value. C.R. describes the level of consistency of judgment of decision-makers. Inconsistency arises when a decision-maker for instance holds the following condition $a_1 > a_2 > a_3$ which suggests that $a_1 > a_3$ but fails to realize this relation in the pairwise comparisons matrix. Decision-makers were asked to repeat the pairwise comparisons for $CR \geq 0.10$.

2.1.3 Synthesizing Judgments

Saaty (2007) described that synthesizing judgments in AHP is done by weighting the elements being compared in the lower level to an element in the next immediate level, referred to as the parent element, by the priority of that element and adding all parents for each element in the lower level. This is referred to as the distributive mode of the AHP. This can be represented in the form

$$w_j = \sum_{i=1}^{n} c_i x_{ij} \tag{4}$$

where w_j is the global weight of alternative j, c_i is the weight of criteria i with respect to the goal, and x_{ij} is the local weight of alternative j with respect to criteria i. Alternatively, in matrix form

$$\mathbf{W}^{\mathbf{T}} = \mathbf{X}\mathbf{C}^{\mathbf{T}} \tag{5}$$

where $\mathbf{W}$ is an mx1 matrix, $\mathbf{X}$ is an mxn $(j \in m, i \in n)$ matrix of alternative weights with respect to each criterion and $\mathbf{C}$ is an 1xn matrix of criteria weights. This synthesized vector of priority weights of alternatives is also termed as the global priority vector.

2.2 Proposed Procedure

In general, the procedure of evaluating input elements in developing SM initiatives using AHP is as follows:

1. Adopt the hierarchical evaluation structure described by Joung et al. (2013) which was eventually the standard SM indicators adopted by US NIST. The structure and its details could be accessed through the sustainable manufacturing indicators repository (SMIR) website (SMIR, 2011) that is managed by the agency. It is composed of three levels which are (from top to bottom) the SM dimension component, the criteria component and the sub-criteria component. A coding system is introduced in this study that assigns alphabetical letters to each level of the hierarchical framework and assigns numbers to the sequence of elements in each level. Goal is coded as A; SM dimensions are coded as B; criteria component is coded as C; and lastly sub-criteria component is coded as D. For instance, employee health and safety, as a sub-criterion is coded as D25. Table 1 shows the decision components and elements along with their corresponding codes. Figure 1 presents the hierarchical structure with the codes applied in this work. Applying this structure and making it as an evaluation framework comprises the general hierarchical evaluation framework adopted in this study as shown in Figure 2. It presents the SM hierarchical structure of Joung et al. (2013) with priorities obtained using the AHP. The proposed framework suggests that the resulting priority ranking in the sub-criteria component is the input in developing SM initiatives.

Table 1. Decision components and their codes

Decision components and elements	**Code**	**Decision components and elements**	**Code**	**Decision components and elements**	**Code**
Evaluation of inputs elements	A	Ozone depletion gas emissions	D3	Materials acquisition	D19
Environmental stewardship	B1	Noise	D4	Production	D20
Economic growth	B2	Acidification substance	D5	Product transfer to customer	D21
Social well-being	B3	Effluent	D6	End-of-service-life product handling	D22
Pollution	C1	Air emissions	D7	Research and development	D23
Emissions	C2	Solid waste emissions	D8	Community development	D24
Resource consumption	C3	Waste energy emissions	D9	Employees health and safety	D25
Natural habitat conservation	C4	Water consumption	D10	Employees career development	D26
Profit	C5	Material consumption	D11	Employee satisfaction	D27
Cost	C6	Energy/electrical consumption	D12	Health and safety impacts from manufacturing and product use	D28
Investment	C7	Land use	D13	Customer satisfaction from operations and products	D29
Employee	C8	Biodiversity management	D14	Inclusion of specific rights to customer	D30
Customer	C9	Natural habitat quality	D15	Product responsibility	D31
Community	C10	Habitat management	D16	Justice/equity	D32
Toxic substance	D1	Revenue	D17	Community development programs	D33
Greenhouse gas emissions	D2	Profit	D18		

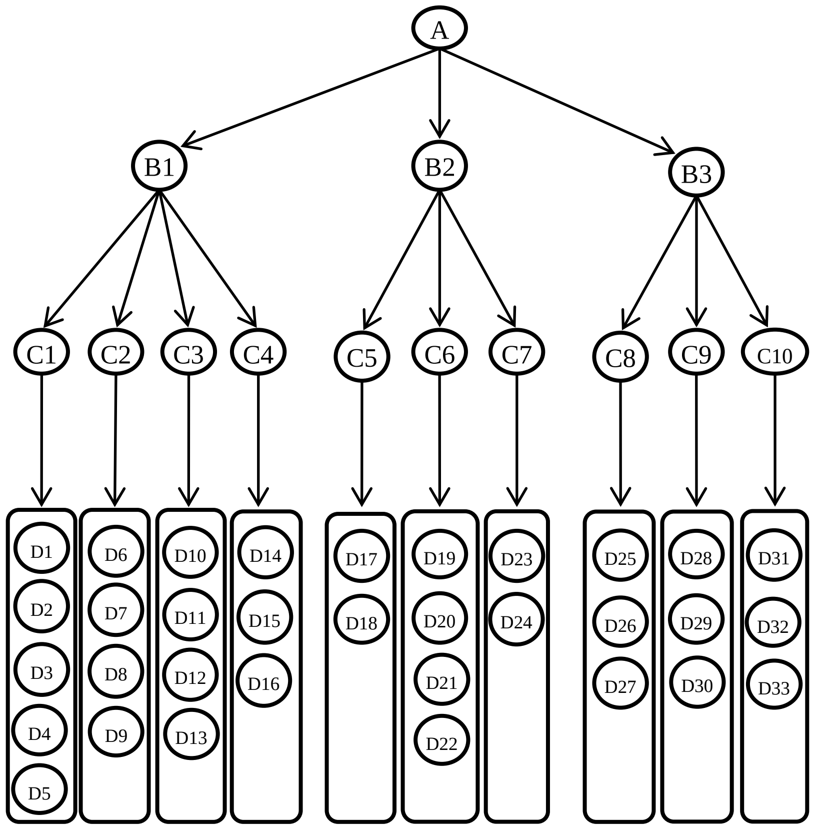

Figure 1. Decision problem of the evaluation of input elements in developing SM initiatives

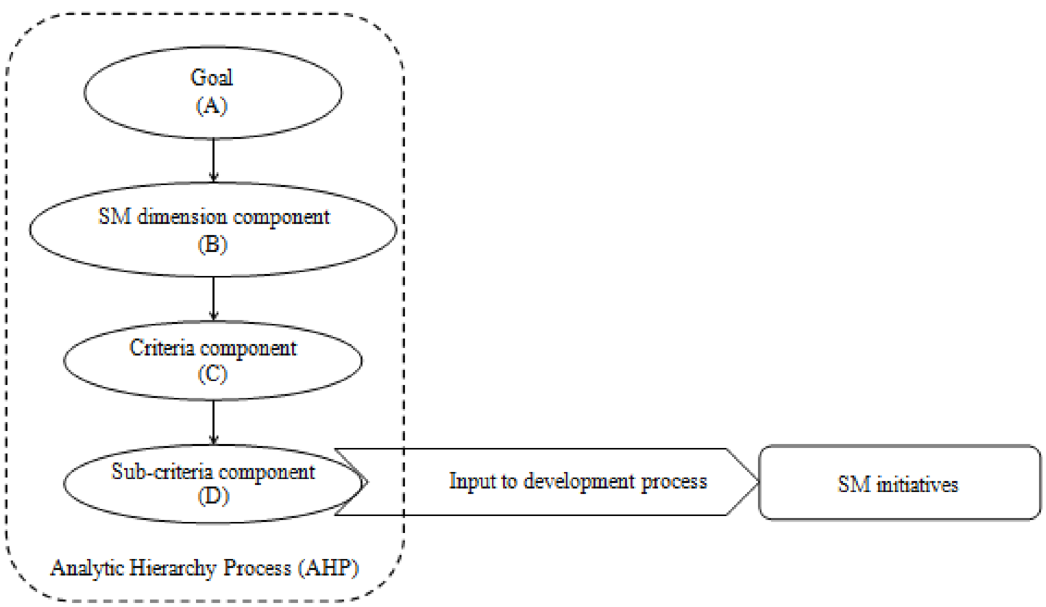

Figure 2. General hierarchical evaluation framework

2. Elicit pairwise comparisons based from the framework developed in 1. In eliciting pairwise comparison, generally we ask this question: "Given a parent element and given a pair of elements, how much more does a given member of the pair dominate other member of the pair with respect to a parent element?" (Promentilla et al., 2006). Saaty's Fundamental Scale presented in Table 2 is used to compare elements pairwise. A group of experts which is composed of four sustainability researchers and three consultants has been invited to elicit judgments through pairwise comparisons using the scale in Table 2. This method is consistent with the works of Promentilla et al. (2006) and Tseng et al. (2009b). The expert group was informed ahead with the purpose of the group discussion and their roles in eliciting judgments.

3. Local priority vectors are obtained by raising a pairwise comparisons matrix to sufficiently large powers, adding row values and normalizing each with the total sum of all the rows (Saaty, 2008). Consistency is checked using equations 2 and 3. Note that C.R. must be less than 0.10 (Saaty, 1980).

4. After obtaining all local priority vectors, judgment is synthesized using equations 4 and 5 to obtain global priorities of each element. Note that this vector is used to rank the elements with their degree of impact or contribution to the goal.

Table 2. Fundamental Scale

Rate	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
2	Weak	between equal and moderate
3	Moderate importance	Experience and judgment slightly favor one element over another
4	Moderate plus	between moderate and strong
5	Strong importance	Experience and judgment strongly favor one element over another
6	Strong plus	between strong and very strong
7	Very strong or demonstrated importance	An element is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	between very strong and extreme
9	Extreme importance	The evidence favoring one element over another is one of the highest possible order or affirmation

3. Results and Discussion

Based from Figure 1, there are three types of pairwise comparisons in this study. The first type describes pairwise comparisons of elements of SM dimensions component with respect to the goal. The second type describes pairwise comparisons of elements in criteria component with respect to their parent SM dimension. Lastly, the third type represents the pairwise comparisons of elements in the sub-criteria component with respect to their parent criterion. A total of 14 pairwise comparisons are required in this study. Note that for the purpose of brevity, we could not present all 14 pairwise comparisons in this paper due to the large amount of space required. Nevertheless, we provide sample pairwise comparisons matrices in the following discussions. A sample pairwise comparison of the first type is shown in Table 3. The question being asked in Table 3 is like this: "Comparing environmental stewardship (B1) and economic growth (B2), which one more dominates the goal (G) and by how much?" The resulting priority vector, λ_{max} and C.R. are shown in Table 3. Table 4 shows a sample of the pairwise comparisons of the second type. The question being asked in Table 4 is like this: "Comparing employee (C8) and customer (C9), which one more dominates social well-being (B3), and by how much?" Finally, Table 5 shows a sample of the pairwise comparisons of the third type. The question being asked in Table 5 is like this: "Comparing employee health and safety (D25) and employee career development (D26), which one more dominates employee (C8), and by how much?"

The following tables present the local priority vectors of each pairwise comparisons matrix with their corresponding maximum eigenvalues and consistency ratio (C.R.). C.R. values range from 0.0 to 0.0732 which satisfy the 0.10 threshold of Saaty (1980).

Table 3. Comparing sustainability dimensions with respect to the goal

A	B1	B2	B3	Local priority vector
B1	1	1/2	1/2	0.200
B2	2	1	1	0.400
B3	2	1	1	0.400

$\lambda_{max} = 3, \text{C. R.} = 0.0$

Table 4. Sample pair wise comparisons of comparing criteria with respect to their parent element

B3	C8	C9	C10	Local priority vector
C8	1	1/2	1	0.250
C9	2	1	2	0.500
C10	1	1/2	1	0.250

$\lambda_{max} = 3, \text{C. R.} = 0.0$

Table 5. Sample pair wise comparisons of comparing sub-criteria with respect to their parent criterion

C8	D25	D26	D27	Local priority vector
D25	1	3	3	0.600
D26	1/3	1	1	0.200
D27	1/3	1	1	0.200

$\lambda_{max} = 3, \text{C. R.} = 0.0$

Table 6, on the other hand, presents the global priority vector of the elements in the sub-criterion component. This normalization process follows the distributive mode of AHP (Saaty, 2008) which is done by multiplying the weight of the sub-criterion with the weight of the parent criterion and the product is then multiplied with the weight of the parent SM dimension. The sum of all these weights is equal to unity.

Table 6. Global priority vector of sub-criteria (input elements to development)

Code	Input elements	Global priority vector
D17	Revenue	0.080
D18	Profit	0.080
D29	Customer satisfaction from operations and products	0.080
D30	Inclusion of specific rights for customers	0.080
D25	Employees health and safety	0.060
D19	Materials acquisition	0.053
D20	Production	0.053
D24	Community development	0.053
D28	Health and safety impacts from manufacturing and product use	0.040
D31	Product responsibility	0.033
D32	Justice/equity	0.033
D33	Community development programs	0.033
D7	Air emission	0.032
D21	Product transfer to customer	0.027
D22	End-of-service-life product handling	0.027
D23	Research and development	0.027
D1	Toxic substances	0.024

Code	Input elements	Global priority vector
D2	Greenhouse gas emissions	0.024
D26	Employees career development	0.020
D27	Employee satisfaction	0.020
D6	Effluent	0.016
D8	Solid waste emission	0.016
D14	Biodiversity management	0.016
D10	Water consumption	0.009
D12	Energy/electrical consumption	0.009
D13	Land use	0.009
D3	Ozone depletion gas emissions	0.008
D5	Acidification substance	0.008
D15	Natural habitat quality	0.008
D16	Habitat management	0.008
D9	Waste energy emission	0.005
D4	Noise	0.005
D11	Material consumption	0.003

It is shown in Table 6 that high priority input elements in developing SM initiatives include revenue, profit, customer satisfaction from operations and products, and inclusion of specific rights to customers. These constitute economic and social dimensions of sustainability. It can be shown that in sustaining manufacturing, initiatives must focus on improving economic performance in terms of higher revenues and profit. This idea conforms to the traditional profit-centered manufacturing. However, along with these profit-centered initiatives, manufacturing firms must keep their customers at the forefront of their agenda. Among key input elements that must be considered are customer satisfaction assessment, customer complaints, product and service information required by procedures and breaches of customer privacy. SM initiatives must focus on effectively integrating these input parameters along with initiatives that relate to economic performance. Note further that the first five high priority input elements also address socio-economic aspects which cover profit-and-customer-centered approaches to cost, employee and customer welfare. One-third of these enhances economic aspects while two-thirds consider social aspects. In the top ten input elements, 37% of them are economic-related, 23% are environmental-related and 40% are social-related. This work suggests that socio-economic issues arising from manufactured products and manufacturing processes are key input parameters in developing SM initiatives at firm level.

4. Conclusion

Evaluating input elements in developing SM initiatives of manufacturing firms is critical in supporting decision-makers to ensure that SM initiatives conform to the demands of sustainability. Such evaluation is a challenge due to a number of criteria that must be considered, along with the subjectivity of these criteria. This paper presents an evaluation framework using the hierarchical sustainable manufacturing indicators structure of the US NIST in the context of the methodology of the AHP. This work shows that high priority input elements include addressing socio-economic issues such as developing initiatives that would enhance revenue and profit while keeping utmost customer welfare in terms of satisfaction from manufactured products and processes and inclusion of specific rights. Along with these, firms must also focus on cost reduction and on highlighting initiatives that improve employee and community welfare. Developing SM initiatives that address socio-economic issues encompassing revenue, profit and cost with customer, employee and community would be a rich area of future research and application. Future theoretical work and empirical studies must be established to support this claim. Another possible extension of this work is to incorporate dependence relationships among elements and components of the decision problem and to address uncertainty in decision-making. Nevertheless, the application of AHP advances knowledge in the evaluation of input elements in developing SM initiatives.

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