FUZZY BASED SUSTAINABILITY INDICATOR FOR PRODUCT DESIGN AND DEVELOPMENT PROCESS

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ABSTRACT

Traditionally, the remedial ‘end of pipe’ control was applied to reduce environmental impact during a product’s entire life. Unfortunately, this method requires too much time to fix the problem rather than preventing it. Therefore, shifting from corrective into prevention act is more essential in preserving our environment. The environmental consideration during design stage is the best preventive action to reduce the impacts. Additionally, economic and social factors also need to be considered in improving a product’s sustainability performance. Research has established the importance of developing a specific tool to fulfill the needs of a sustainable product. Several tools are available such as Eco Indicator 95 and 99, Life Cycle Index, Ten Golden Rules etc., however most of these tools only focus on one or two sustainability elements whereas sustainability requires the consideration of the environment, economic and social elements and the proposed method considers all three. Furthermore, sustainability elements involve various parameters including pollution, cost and energy, among others which then increase the complexity in decision making process. Subsequently, the quantitative and qualitative data of sustainability parameters further complicate this evaluation. In this study, a comprehensive method for evaluating sustainability is proposed to assist engineers and designers in making better decisions. A fuzzy approach has been applied in the sustainability evaluation because of its capability in reducing data uncertainty and simultaneous handling of qualitative and quantitative data. The sustainability input parameters from life cycle inventory databases such as European Life Cycle Database, Ecoinvent and others are converted into an index value which is known as sustainability indicator. A case study involving an automotive headlamp, passenger car and selection of a sustainable electrical power generation plant is presented. The results are also compared with Eco Indicator 99 to validate the accuracy of the assessment. From the comparison, it is found that the result of the developed sustainability indicator agrees with the Eco Indicator 99 approach. Therefore, the developed sustainability indicator is able to indicate the sustainability performance of a product and also highlight the critical area for improvement.

ABSTRAK

Secara tradisi, langkah pemulihan '*end of pipe*' dilaksanakan bagi mengurangkan impak sesuatu produk terhadap alam sekitar. Malangnya, cara ini memerlukan tempoh masa yang lama untuk membaiki punca masalah daripada cuba menghindarinya. Oleh itu, untuk memelihara alam memerlukan perubahan tindakan daripada membaiki kepada menghindari. Cara yang terbaik untuk mengurangkan impak adalah dengan mengambil kira faktor alam sekitar semasa proses rekaan sesuatu produk bermula. Sementara itu, elemen ekonomi and sosial juga perlu di beri perhatian untuk meningkatkan kelestarian sesuatu barangan. Kajian telah menunjukkan kepentingan untuk membangunkan kaedah tersendiri bagi menghasilkan barangan lestari. Antara kaedah yang boleh digunakan ialah *Eco Indicator 95* dan *99*, *Life Cycle Index*, *Ten Golden Rules* dan lain-lain yang mana kebanyakannya hanya mengambil kira satu atau dua elemen kelestarian sedangkan ia memerlukan aspek keseluruhan seperti alam sekitar, ekonomi dan sosial dan kaedah yang dicadangkan mengambil kira ketiga-tiganya. Tambahan pula, kelestarian melibatkan pelbagai kriteria seperti pencemaran, kos, tenaga dan lain-lain yang mana boleh meningkatkan kesukaran dalam proses membuat keputusan. Dengan adanya data kuantitatif dan kualitatif lebih menyukarkan lagi proses penilaian ini. Didalam kajian ini, langkah yang mudah untuk menilai kelestarian diperkenalkan bagi membantu jurutera dan pereka dalam membuat keputusan yang terbaik. Kaedah "*Fuzzy*" telah digunakan didalam penilaian kelestarian kerana ia mampu mengurangkan ketidaktentuan data dan mampu menilai data dalam bentuk kualitatif dan kuantitatif. Kriteria lestari masukan daripada pangkalan data seperti *European Life Cycle Database, Ecoinvent* dan lain-lain ditukarkan kepada nilai indek yang kemudiannya dinamakan sebagai penunjuk kelestarian. Kajian kes tentang lampu hadapan kenderaan, kereta penumpang dan pemilihan loji kuasa elektrik lestari telah dijalankan. Hasil keputusan daripada kajian kes dibandingkan dengan *Eco Indicator 99* untuk mengesahkan keberkesanan penilaian. Daripada hasil perbandingan, didapati ada keseragaman keputusan antara penunjuk kelestarian dan *Eco Indicator 99*. Oleh itu, penunjuk kelestarian yang dibangunkan mampu menilai potensi kelestarian sesuatu barangan serta mampu menunjukkan aspek kritikal untuk penambahbaikan.

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LIST OF ABBREVIATIONS

ABS	-	Acrylonitrile butadiene styrene
AHP	-	Analytical Hierarchy Procedure
BOD	-	Biochemical oxygen demand
BOM	-	Bill of material
C	-	Degree celcius
Cd	-	Cadmium
CF	-	Carbon Footprint
CFC	-	Chlorofluorocarbon
$CFCl_3$	-	Triklorofluorometana (CFC-11)
CF_2Cl_2	-	Diklorodifluorometana (CFC-12)
$C_2F_3Cl_3$	-	Triklorotrifluoroetana (CFC-113)
$C_2F_4Cl_2$	-	Diklorotetrafluoroetana (CFC-114)
C_2F_5Cl	-	Kloropentafluoroetana (CFC-115)
CH_4	-	Methane,
CO	-	Carbon monoxide
CO_2	-	Carbon dioxide
CoC DFE	-	Center of Competence for Design for Environment
COSHH	-	Control of Substances Hazardous to Health Regulation
DfAD	-	Design for Assembly and Disassembly
DfE	-	Design for Environment
DfX	-	Design for X
EC	-	European Commission
EI 99	-	Eco-indicator 99
ELCD	-	European Life Cycle Database

ELV	-	End of Life Vehicle
EoL	-	End of Life
EPD	-	Environmental Product Declaration
ERPA	-	Environmental Responsible Product Assessment
EU	-	European Union
GUI	-	Graphic of user interface
H	-	High
HDPE	-	High-density polyethylene
HFC	-	Hydrofluorocarbon
Hg	-	Mercury
HSE	-	Health, safety and environment
IARC	-	International Agency for Research on Cancer
IPCC		Intergovernmental Panel on Climate Change
IPP	-	Integrated Product Policy
ISO	-	International Standard Organization
L	-	low
LCA	-	Life cycle assessment
LCI	-	Life Cycle Inventory
LCIA	-	Life Cycle Impact Assessment
LCM	-	Life Cycle Management
LInX	-	Life Cycle Index
LM	-	Low to medium
kg	-	Kilo gram
kJ	-	Kilo joule
km	-	Kilometer
kWatt	-	Kilo watt
kWh	-	Kilo Watt . hour
L	-	Liter
LCA	-	Life Cycle Assessment
LEBS	-	Low emission boiler system
M	-	Medium
m	-	Meter
MDCM	-	Multi Criteria Decision Making

MH	-	Medium to high
MJ	-	Mega Joule
MS	-	Malaysia standard
NH_3	-	Ammonia
NMVOC	-	Non methane volatile organic compound
NO_2	-	Nitrogen dioxide
NOx	-	Nitrous oxide
N_2O	-	Nitrogen oxide
NREL	-	National Renewable Energy Laboratory
NSPS	-	New Source Performance Standard
O_3	-	Trioxygen or ozone
OP	-	Oil point
Pb	-	Lead
PBB	-	Polybrominated biphenyls
PBDE	-	Polybrominated diphenyl ethers
PBT	-	Polybutyleneterephthalate
PC	-	Polycarbonate
PCB	-	Polychlorinated biphenyls
PCT	-	Polychlorinated triphenyls
PET	-	Polyethylene terephthalate
PM_{10}	-	Particulate matter less than 10µm
PP	-	Polypropylene
PU		Polyurethane
PVC	-	Polyvinyl chloride
REACH	-	Registration, Evaluation, Authorisation and Restriction of Chemicals directive
RM	-	Ringgit Malaysia
RoHs	-	Restriction of Hazardous Substances
SIRIM	-	Standards and Industrial Research Institute of Malaysia
SLCA	-	Simplified Life Cycle Assessment
SO_2	-	Sulfur dioxide
SPM	-	Suspended particulate matter
t.km	-	Ton kilometer

US	-	United States
VOCs	-	Volatile organic compounds
WEEE	-	Waste of Electrical and Electronic Equipment directive
WHO	-	World Health Organization

LIST OF SYMBOLS

d	-	Current value
d_{max}	-	Maximum target / reference value
d_{min}	-	Minimum target / reference value
u	-	Normalization value
AND	-	Fuzzy operator (minimum)
OR	-	Fuzzy operator (maximum)
I_{gw}	-	Global warming index
I_{acid}	-	Acidification index
I_{eutro}	-	Eutrophication index
I_{cost}	-	Cost index
I_{energy}	-	Energy index
$I_{material}$	-	Material index
I_{health}	-	Human health index
I_{hm}	-	Heavy metal index
$I_{carcinogen}$	-	Carcinogen index
I_{envi}	-	Environmental index
I_{eco}	-	Economic index
I_{social}	-	Social index
$I_{sustain}$	-	Sustainability index
μ_L	-	LOW degree fuzzy membership function
μ_{LM}	-	LOW to MEDIUM degree fuzzy membership function
μ_M	-	MEDIUM degree fuzzy membership function
μ_{MH}	-	MEDIUM to HIGH degree fuzzy membership function
μ_H	-	HIGH degree fuzzy membership function

$\mu_L(x)$	-	Degree of membership for x input value of LOW fuzzy linguistic variable
$\mu_{LM}(x)$	-	Degree of membership for x input value of LOW to MEDIUM fuzzy linguistic variable
$\mu_M(x)$	-	Degree of membership for x input value of MEDIUM fuzzy linguistic variable
$\mu_{MH}(x)$	-	Degree of membership for x input value of MEDIUM to HIGH fuzzy linguistic variable
$\mu_H(x)$	-	Degree of membership for x input value of HIGH fuzzy linguistic variable
x	-	Fuzzy input variable
L	-	Fuzzy linguistic variable for LOW degree
LM	-	Fuzzy linguistic variable for LOW to MEDIUM degree
M	-	Fuzzy linguistic variable for MEDIUM degree
MH	-	Fuzzy linguistic variable for MEDIUM to HIGH degree
H	-	Fuzzy linguistic variable for HIGH degree
R	-	Number of fuzzy rule
n	-	Degree of input variables or number of input degrees
v	-	Number of input variables or number of *facts* in the premise
$X*$	-	Defuzzified output or defuzzification
$N_i(x)$	-	Aggregated membership function
I_j	-	Index of stage 2 for j-th categories or sustainability element index
I_{ij}	-	Sub-element of sustainability index
w	-	Weightage
i	-	Sustainability sub element (global warming, pollution, eutrophication, acidification, resource, energy, cost, human health, heavy metal and carcinogen
j	-	Sustainability element (environment, economic and social)
w_{gw}	-	Weight of global warming index
w_{acid}	-	Weight of acidification index
w_{eutro}	-	Weight of eutrophication index

w_{cost}	-	Weight of cost index
w_{energy}	-	Weight of energy index
$w_{material}$	-	Weight of material index
w_{health}	-	Weight of human health index
w_{hm}	-	Weight of heavy metal index
$I_{sustainability}$.	-	Sustainability indicator
w_{envi}	-	Weight of environment
w_{eco}	-	Weight of economic
w_{social}	-	Weight of social
I_k	-	Life cycle index
k	-	Product life cycle (raw material extraction, manufacturing, transportation, usage and end of life
I_{ik}	-	Sub sustainability element index during k life cycle
i	-	Sub sustainability element
I_{raw}	-	Life cycle index during raw material extraction stage
I_{mfg}	-	Life cycle index during manufacturing stage
$I_{transport}$		Life cycle index during transportation stage
I_{usage}		Life cycle index during usage stage
I_{eol}		Life cycle index during end of life stage

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Every year the human population grows, creating a negative impact on the Earth. As the population grows, more domestic and non-domestic products are produced due to higher demand. In addition, the mass production of products in greater volumes heavily consumes energy and raw materials. As a result, the natural resources for the future generation are depleting. Meanwhile, huge amounts of waste and emissions are released during manufacturing, use, and end of the product life cycle. The chemical and hazardous wastes from industries contaminate the natural water stream such as rivers and seas, resulting in harmful effects on humans, plants, and animals. Additionally, more land area is required to provide landfill for solid waste disposal, buildings, and houses. The entire situation decreases the sustainability of the world.

Sustainability can be defined as “a notion of viable futures,” which includes aspects of the environment, public health, social equity, and justice (Blevis, 2007). The detailed definition of sustainable development described by Karlsoon and Luttropp (2006) is a “process of change in which the exploitation of resources, the direction of investments, the orientation of technical development and institutional change are all in harmony with the enhancement both the current and future potential to meet human needs and aspirations." In other words, current activities eventually will have an impact on the next generation. As such, the efficient management of activities is crucial to minimize the negative impact on the future generation

Sustainability depends on the size of population and impact. As the population and impact continue to grow, the world becomes less sustainable. To improve or maintain sustainability is a big challenge, because the population keeps growing every year (United Nations, 2009). Another alternative approach of maintaining world sustainability is to reduce the level of impact by designing and producing sustainable products that have less impact on the future generation.

According to Ljungberg (2007), a sustainable product is a product that has little impact on the environment during its life cycle. A sustainable product can be produced only by considering the sustainable aspects (i.e., environmental, technical, economic, and social) in the design process. Design from the sustainability perspective can be defined as an "act of choosing among or informing choices of future ways of being" (Blevis, 2007). Designing a sustainable product is apparently easy, but the actual production of a successful sustainable product is difficult, as numerous criteria need to be considered. Ljungberg (2007) has simplified the successful product with seven chains that are linked to each other, as shown in Figure 1.1. The seven rings in the sustainability chain circle can be described as follows:

i. *Material*. The material and energy consumption is minimized, and renewable materials are used as much as possible.

ii. *Economy*. Product and service are cost efficient and comparable to similar products.

iii. *Design*. Design is for the environment and users, as well as for recycling.

iv. *Market*. Products are developed and designed according to the market need and target user.

v. *Equity*. Trading equity and the impact on the local and global community are considered.

vi. *Technology*. The extraction of raw materials, and the production, lifetime, and quality of products are optimized.

vii. *Ecolog*y. Emissions and wastes are eliminated, and the environmental impact is minimized.

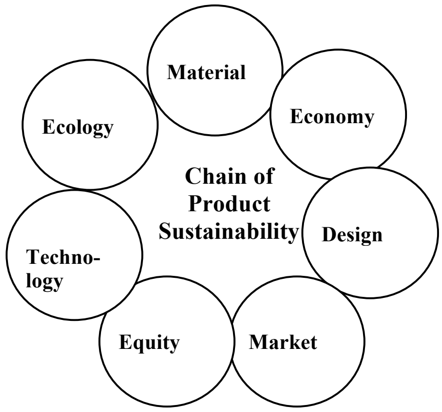

Figure 1.1 Chain of product sustainability (Ljungberg, 2007)

Some benefits are present in producing a sustainable product. A sustainable product not only minimizes the environmental burden, but also meets the market needs and fulfills the national and international legislation. As environmental awareness is now emerging, most countries adapt environmentally conscious legislation in product development. In 2000, the European Union (EU) directive was developed by considering the end-of-life vehicle (ELV). The automotive industry is a concern of the EU because of its major manufacturing activities in the world. In addition, the automotive industry involves several suppliers and other parts manufacturers in producing a vehicle, and they have to follow the regulation of the EU directive (Gerrard and Kandlikar, 2007). As a result of such regulation, the automotive industry is expected to have a huge contribution in improving world sustainability

The EU directive on ELVs was designed to reduce the waste disposal problem caused by automotive industries. Article 7(b) of the ELV directive states, "no later than 1 January 2015, for all end-of life vehicles, the reuse and recovery shall be increased to a minimum of 95% by an average weight per vehicle". Within the same time limit, the re-use and recycling shall be increased to a minimum of 85% by an average weight per vehicle and year" (European Parliament, 2000). All the vehicle producers and suppliers must comply with the legislation to allow them to market their products to all European countries by 2015. Thus, most vehicle manufacturers have to shift toward design for sustainability. Some of the big automotive players, such as BMW, Toyota, and Opel, are already adopting sustainable perspectives

Today, consumers' product preference is not only based on functionality, quality, and cost, but on the environmental aspect as well. Consumer awareness on environmental issues is increasing and they are willing to pay for "green" or environmentally conscious products, and this phenomenon creates new opportunities in marketing strategies. Developing sustainable products can be the best strategy to survive in today's market. Moreover, developing green products will increase the sales volume and profits. For example, BMW produced a vehicle whose components can be reused, recycled, and remanufactured by considering the end-of-life of the product (BMW Group, 2008). Other manufacturers such as Toyota are taking a different route in product sustainability by integrating universal design in their cars to fulfill the social aspect, which is one of the elements of sustainability (Toyota Motor Co., 2007). Consequently, a sustainable product can be a competitive advantage in the current market.

The sustainable perspective must be integrated into the design process at the early stage of new product development to produce a sustainable product. The adaptation of a sustainability perspective during the design phase helps in producing a sustainable product with the ability to minimize waste and allow product recyclability and longevity.

1.2 Problem Definition

Sustainability is proportionally inversed to the population and impact. Reducing the world population is difficult; nevertheless, reducing the impact toward the environment and humans is possible. One solution is to reduce the waste by reusing, remanufacturing, and recycling. Another approach is to apply good manufacturing practices by increasing process efficiency, reducing energy use, and promoting a zero emission process. These measures are usually adopted at the current life cycle stage. For example, recycling is undertaken only after the end-of-life of a product, and energy reduction is only considered at the manufacturing and use stage. In the short term, these approaches seem to be effective; however, these actions should be undertaken at the earliest stage possible to maintain long-term sustainability. These actions can be undertaken possibly during the product development or product design phase.

At the design stage, the impact of each life cycle stage of the product toward sustainability will be evaluated. With regard to the environmental aspect, the new product must not produce and emit substances that have a high impact toward global warming, biodiversity, and toxicity. In relation to the economic factors, the product must be designed with minimum cost by reducing the use of materials, energy, and other resources. At the same time, human health and safety must also be considered during the design stage through methods such as eliminating the use of hazardous materials and reducing nuisance by reducing noise level and particulate matter while manufacturing the product.

Various legislations, such as the EU directive on the end of life vehicle (ELV), restriction of hazardous substances (RoHS), and Kyoto Protocol, are being introduced to protect the world sustainability. By enforcing such regulations, the manufacturers have to comply to enable them to market their products globally. Indirectly, these requirements have raised the awareness of the manufacturers, shifting their perception toward producing environmentally conscious products. Some examples of design methodologies that assist designers in producing green products are design for recycling, design for assembly and manufacture, design for environment, and life cycle design. However, most of these current methods only focus on the environmental aspect, whereas sustainability requires a broader area such as the inclusion of economic and social aspects. Thus, an opportunity arises for researchers to explore a new research area to develop a methodology for sustainable product design.

The sustainable perspective must be integrated at the early stage in the product development process to produce a sustainable product. In this case, the role of the designer is important in achieving this objective by considering the inclusion of sustainable elements in their design (Yang and Song, 2006). However, inclusion of the sustainable perspective is difficult because of the designers' lack of knowledge on environmental, economic, and social issues. As a result, evaluating their design in terms of sustainability is impossible. Thus, a comprehensive tool is necessary to assist the designers in designing and developing a sustainable product, and at the same time, enabling the measurement of the sustainability level of design. By evaluating product sustainability, the designers can easily identify the weakness of their design for further improvement and select the best sustainable design alternative (Almeida and Barros, 2006)

1.3 Research Questions

The research questions of this study are as follows

i. Is there any methodology on product sustainability assessment that includes all the three main aspects (environmental, economic, and social) and cost analysis in their assessment?

ii. How can both qualitative and quantitative data of sustainability parameters be evaluated?

iii. Is the sustainability indicator able to identify the weaknesses and strengths of a product, which then can aid product improvement?

iv. Is the indicator value able to visualize the sustainability performance?

1.4 Objectives of the Study

The following are the objectives of this study:

i. To develop a methodology for a sustainability indicator that will be used to assess the sustainability performance of a product;

ii. To integrate the environmental, economic, and social aspects in the evaluation of the sustainability indicator;

iii. To apply the fuzzy inference technique in the evaluation and determine the sustainability performance of a product; and

iv. To verify the effectiveness of the sustainability indicator methodology using several case studies.

1.5 Scope of the Study

The scopes of the study are as follows:

i. Three aspects of sustainability elements, such as environmental, economic, and social factors are evaluated in the proposed methodology.

ii. The boundary of analysis of the developed methodology is based on the cradle-to-grave approach.

iii. The international standard for life cycle assessment, ISO 14040:2006 (Life Cycle Assessment) is used as the guideline in developing the sustainability indicator.

1.6 Significance of the Study

The significance of the current study are as follows:

i. A new concept in product development is developed by considering sustainable perspectives in the design process. The three elements of sustainability, namely, environmental, economic, and social aspects, are considered in the product development phase.

ii. The study is used to provide assistance in developing a sustainable product and maintain world sustainability. The sustainability indicator is a method for measuring the sustainability level of a product or process. By knowing the sustainability performance, the critical area can be identified and the necessary action can be taken for further improvement. Thus, the sustainability indicator helps the designer to produce a sustainability conscious product.

iii. The outcome of the study is expected to be applied in a new design process to compete in the current market. Awareness of environmental issues and knowledge is emerging among the public through various advertisements on the internet and in the multimedia environment. The customers' product preference is now shifting from price concern to environmental interest. Customers are willing to pay more for an environmentally conscious product, thus creating a new market trend. As such, the developed sustainability indicator is very useful in assisting the manufacturer in marketing a product that has low environmental burden, less cost, high profit, and less impact on the social aspect.

iv. The study can help the designers and manufacturers meet the national and international legislations, such as the EU directive on the ELV, RoHS, and Malaysia environment standards, for their products. Currently, most countries are aware of world sustainability and the regulations developed to maintain this sustainability. In Malaysia, the Environmental Act 1974 was enacted, which covers the waste, hazardous substances, and gaseous emissions, among others. These legislations become a constraint for most manufacturers and designers to create and market their products. The developed fuzzy sustainability indicator can be used to help the designer and manufacturer meet the local and international requirements. Criteria such as solid waste, greenhouse gaseous, heavy metal, and chemical waste are taken as the input parameters for sustainability evaluation. Accordingly, measuring the sustainability performance also guides the designers in meeting the regulation.

v. The sustainability evaluation method is to be used in decision making and design improvement of a new or existing product. Hence, this method guides the designer in developing a product with a high sustainability performance.

1.7 Assumptions

The proposed sustainability indicator is implemented under several assumptions:

i. The sustainability parameter evaluated depends on data availability, and represents the sustainability performance of the product.

ii. The life cycle database used to determine the input value of the sustainability parameter is valid and credible.

iii. The manufacturing cost is assumed to be the labor cost per unit part or product.

iv. The benefit from recycling material is assumed to be the profit gain from selling the material to the recycling company with the assumption cost of RM 0.30 per kilogram.

v. The transportation cost is assumed to be the cost of fuel use to transport the product.

1.8 Organization of the Thesis

This thesis consists of seven chapters. Chapter 1 presents the background of the study, problem definition, objectives, and scope of the study, assumptions used, and significance of the study.

Chapter 2 presents a detailed literature review covering a number of relevant topics, such as the concept of sustainability, product sustainability, sustainability elements and sub-elements, and current available methods for measuring sustainability.

Chapter 3 elaborates several topics related to sustainability assessment, such as the sustainability parameter, boundary of analysis, and concept of indicator, to name a few. The local and international regulations and fuzzy inference system are also discussed in this chapter.

Chapter 4 discusses a methodology for this research, which consists of the development of the sustainability indicator. This chapter also discusses the fuzzy technique used in the evaluation of product sustainability. In addition, it presents the steps required to develop fuzzy sustainability assessment.

Chapter 5 presents the application of the developed fuzzy sustainability assessment (sustainability indicator) method to analyze the sustainability performance of the product.

Chapter 6 discusses the work that has been carried out in developing the methodology of the fuzzy sustainability assessment. This chapter provides the whole view of the research with its ultimate result.

Lastly, the Chapter 7 provides a summary of the main research outcomes of this thesis, including the research implications. This chapter also reveals opportunities for future research.

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