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RESEARCH PAPER

Selection of the Most Effective Deliverables in the Sustainability of the Product Design and Development Process Group Employing Hybrid Delphi-GAHP and COCOSO Method

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Abstract

Over the past decade, establishing sustainability has become the center stage in manufacturing products as most elements of sustainability meaning economic, social and environmental pillars are improving. However, developing processes leading to product sustainability throughout its life cycle, especially in the new product development process groups, is still in its infancy. The present study focuses on ranking the product development process groups and identifying the most effective one in product sustainability through Delphi-GAHP and COCOSO methods. To carry out this task, product life cycle, the main new product design and development process groups, gateway planning, deliverable items, and product sustainability pillars have been introduced and the necessary data has been collected with the help of automotive industry experts. The most effective process group in product sustainability was selected and the deliverables in the selected process group were ranked to isolate the most effective deliverable item in product life cycle sustainability. Based on the research findings, the product planning and definition process group has the highest rating score and the ability to create sustainability pillars with the highest effectiveness in sustainable end product development. In addition, this study showed that the development and application of sustainability components in one of the deliverables of this process group (target book) has the greatest impact on creating sustainability at different stages of the product life cycle. Evidently in future research, the findings of this study can be employed in establishing sustainability in product development processes by developing the attributes and components of this new deliverable item.

Keywords:
Deliverables;
Product Design and Development Process;
Gateway Planning;
Sustainability;
Product Features;
COCOSO Method

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Nomenclature

Variable	Descirption	Unit	Variable	Description	Unit
IDS	Initiation and description of product and process macro strategies	Quantitative and qualitative data to pass through each gate way	*SAW*	Simple weighted sum	Numerical data
SPNA	Strategic planning and needs analysis gateway		*WPM*	Weighted product method	Numerical data
FPDS	Finalization of product and style definition and first step style selection gateway		r_{ij}	The normalisation of criteria values	Numerical data between 0 to 1
PDSL	Product definition at system level gateway		S_i	Weighted sum	Numerical data
FSCD	Finalization the physical style and concept design gateway		P_i	Weighted Multiplication	Numerical data
DCPE	Design check out and prototype evaluation		k_{ai} , k_{bi} , k_{ci}	Three appraisal score strategies	Numerical data
CDPSVP	Completing the design of powertrain and Start making validation prototype		λ	Coefficient	Numerical data between 0 to 1
CDBT	Completing the design of Body and Trim		k_i	Sum of geometric mean and arithmetic mean of 3 strategies	Numerical data
CPV	Completing the manufacture of prototypes and initiating the validation tests		x_{ij}	Evaluation of the i option based on the criterion j	Numerical data
CDCIT	Completing the design changes and the initiation of testing		x'_{ij}	The geometric mean of the opinions of experts	Quantitative and qualitative data
CTITM	Completion of testing and initiation of trial manufacture		G_i	The product development processes group	-
IBPFMP	Initial batch production and finalization of manufacture and process		A_i	The product life cycle stages	-
FPPQ	Final product and process quality		*GAHP*	Group-Analytic Hierarchy Process	-
FRLL	Feedbacks and records of the learned lessons		*COCOSO*	Combined Compromise Solution	Multi-criteria decision making technique

Introduction

Over the last few years, the subject of product sustainability has received considerable attention due to matters such as maintaining and improving the status of the organization in the competing market, meeting the growing needs of customers, increasing legal requirements in order to protect the environment and society, as well as economic goals for optimizing the production process and reducing costs. Hence, product sustainability and achieving an optimal combination of the three economic, environmental and social pillars in all stages of the product life cycle from the stage of raw material extraction to production, use, and post use, has been extensively studied.

Moreover, considering the fact that the new product development process plays a crucial role in product sustainability, it has been regarded as a deciding factor in this research. Consequently, one can say sustainable product development is for the economic, environmental, and social pillars to be taken into account in all stages of the product life cycle. On the other hand, the complexities of product and industrial technology have created additional challenges in how companies go about product design and development affecting the entire product life cycle and processes related to it. As a result, companies have been forced to focus on the concepts of sustainability in the product life cycle.

The present study identifies the most effective product development process group and its most efficient deliverables and output. The review of literature introduces the main concept of the study and defines concepts such as new product design and development process, gateway planning method, sustainability, product life cycle management, outputs and acceptable items in a gateway system, sustainable design and development. In the second section, the research method and problem statement are presented, followed by demonstrating calculations in the third section to determine the priorities of the process group. The results, conclusion, and suggestions are presented in the sections.

The issue addressed in this study is to introduce and prioritize the main process groups of new product design and development based on the principles of sustainability at different stages of the product life cycle, and identifying the most important deliverable items in the selected process group, which ultimately, may result in final product sustainability.

As can be seen in the review of the literature, many research and studies have been conducted on the development of sustainability in new products; but, none on the subject of revising the process of product design and development in a gateway planning system and deliverables. According to studies on product design and development process, sustainability and its elements, product life cycle management, and product attributes, no research has been conducted on evaluating and selecting the most effective process group and its deliverables in order to establish final product sustainability.

In other words, through reviewing the literature and research conducted on the role of product design and development in manufacturing a sustainable product and analyzing the various components and outputs in each stage of product development processes, the present study pursues an approach for identifying the most effective deliverables in product development processes based on sustainability pillars. We are confident that if the economic, social, and environmental pillars and criteria were to be executed in this particular selected process group and its deliverables, gradually, its effects would transpire in all other processes and deliverables. The output products of the processes suggested in this study will have more sustainability in their life cycle and certainly, the prioritization methods proposed will aid the selection of the most effective documentation in product development processes.

Review of literature

According to Waage, defining, planning, and designing a new product is a creative process that addresses customer needs, corporate requirements, and the environmental constraints of governmental agencies through four basic steps, i.e. problem definition, Conceptual design, initial design and detailed design [1]. All requirements must be delivered through these four steps. Furthermore, considering the fact that approximately 70% of the product cost and 80% of product quality is established in the definition, planning, and product design stage, this particular stage has become a major challenge for manufacturing companies. As a result, reference models for new product design and development were developed, the most important of which include the OMG for Product Life Cycle Management (PLM), INCOSE Systems Engineering Handbook Standards, Advanced Product Quality Planning (APQP), and Development Process Methodology.

The products were developed by a committee of companies Ford, General Motors, and Chrysler- with a specific application in the automotive industry on the basis of system engineering concepts and development of ISO 4430-103 and ISO 10007 (2003 edition).

One of the developed models is the product development process model based on the APQP standard framework, which has been shaped by new product design and development centers in various companies. According to APQP standard and current procedures in the majority of design companies, the main product development process groups are product definition and product planning process group, detailed design and product development process group, design and development manufacturing process group (Design of manufacture processes, molds and tools for new product manufacturing), product and manufacturing process group, evaluation and validation process group, and production process group.

Moreover, the product design and development process group basically consists of conceptual design, detailed design, production of drawings and engineering documents, manufacture and assembly design, design approval and review, prototype manufacture, and initial control design. The process of producing engineering drawings is the procedure of determining the technical specifications of components and assemblies.

Through applying engineering changes and the process of analyzing failure modes and their effects on design (DFMEA) and the manufacturer design and development process group, standards and processes for testing are designed and components and products are validated. The sub-processes of layout design, process flow diagram, analysis of failed cases and its effects on the process, pre-control program production are carried out according to the instructions of production processes, analysis plans of the system, and evaluation of process capability.

Finally, the product and manufacture process validation process group is comprised of product or process quality system validation processes, layout validation, process flow chart, specification matrix validation, pre-production control program validation, process instruction validation, and analytical design validation, the system that measures and validates the processes.

Additionally, in product design and development planning exists a concept known as gateway and gateway planning, which is used as one of the pillars of monitoring the various stages of the product design and development process.

Each gateway is a stage of project implementation, through which a set of project activities, inputs and outputs and deliverables must be realized, and to execute each gateway is to realize and provide the deliverable items and gain the approval of stakeholders. In fact, a gate review session is held at the end of each gate in order to review and revise the activities and items delivered through that certain gate.

Based on the APQP reference, Fig. 1 illustrates the four main phases of product development processes, the main activities done in each of these processes, and the designated gateways to pass each stage.

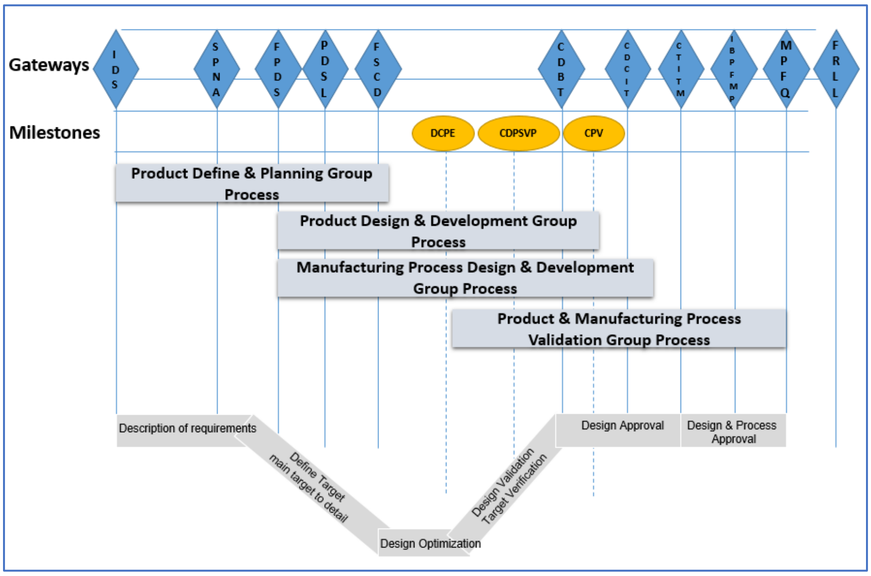

Fig. 1. New product design and development process groups in a gateway system

As demonstrated in Fig. 1 and based on the research and evaluation of the processes of the studied car company, the gateways of a new automobile design and development project incorporate the following; first, initiation and description of product and process macro strategies gateway (IDS), in which the official initiation of studies for a new product project is realized by altering a general product plan into a specific product plan. Second, strategic planning and needs analysis gateway (SPNA) as the first checkpoint where performance compatibility of product and process is examined. Third, finalization of product style and definition. Next is the first step-style selection gateway (FPDS) that consists of definition at the product level and selecting some physical prototypes 2.5. Then, there is product definition at system level gateway (PDSL) that includes the definitions at the level of automobile systems and the selection of the final style based on the physical prototype 1/1. Next is finalizing the physical style and concept design gateway (FSCD) in which the product is defined at all automobile, system, and components levels. There is a design check out and prototype evaluation milestone gateway as well, (DCPE) in which the manufactured prototype's validation is initiated. The next gateway is completing the design of powertrains, and then, starting the validation prototype gateway (CDPSVP) that consists of the initiation of manufacturing the validated prototypes. Completing the design of the body and trim for industrialization and validation gateway (CDBT) is next. Afterward comes completing the manufacture of prototypes and initiating the validation tests gateway (CPV). Completing the design changes and the initiation of testing the equipment and molds gateway (CDCIT), completion of testing and initiation of trial manufacture gateway (CTITM), initial mass production and finalization of manufacture and process gateway (IBPFMP), final product and process quality achievement (FPPQ), and feedbacks and records of the learned lessons gateway (FRLL) are the following gateways.

All in all, approximately 80 deliverables have been defined based on the collected data and researchers' experience in the new product design and development process. In a gateway system, if the pillars of sustainability are applied in each of these deliverables, significant and fundamental steps can be taken in order to provide a reference model for the process of designing and developing a brand new sustainable product.

According to the definition of the World Committee on Environment and Development (WCED), sustainable product development involves meeting the current needs of customers without compromising the ability of future people to meet their own needs. In 1994, the US Environmental Protection Agency (EPA) defined sustainability as customer satisfaction with current and future economic, social, and security needs without compromising the natural and qualitative characteristics of the environment.

The R3 method was proposed by Badurdeen et al. to balance economic, environmental, and social aspects with the intention of designing product sustainability [2]; therefore, in order to focus on the environmental aspect, factors such as consumption reduction, reuse, and recycling of waste were taken into account. However, this method was not a comprehensive approach and did not include all four stages of the product life cycle, meaning the stages of pre-production, production, use, and post-use.

Azapagic et al. believed that with identifying the criteria of sustainability and its important indicators, product sustainability throughout its life cycle is achievable [3]. Additionally, assessing the sustainability of any design and identifying vital points in the life cycle would lead to a more sustainable final product.

In another approach, Jayal et al. describe the design philosophy and methodology for X, which focuses on improving the sustainability of products at different stages of the life cycle [4]. This design method includes design for the environment, design for the community, design for disassembly, design for recycling, design for equipment, design for manufacture, and design for performance. On the other hand, according to Jawahir, the R3 method is not a wide-ranging approach and in order to solve this problem [5], Jawahir developed a new method to create a framework for sustainability design. As presented in Table 1, in Jawahir's method, design for sustainability is divided into 6 main groups and 32 sub-groups.

Table 1. Product Design Elements for sustainability [5]

Design for Enviromental Impact	Life-cycle Factor	Design for Manufacturability	Manufacturing Method
	Envirometal Factor		Packaging
	Economical Balance and Efficiency		Assembly
	Reginal and Global Impact		Storage
Design for Recyclability/ Manufacturability	Disassembility		Transportation
	Recyclability	Design for Resource Utilization and Economy	Energy Efficiency/Power Consumtion
	Disposability		Material Utilization
	Remanufacturability /Reusability		Use of Renewable Source of Energy
Design for Societal Impact	Operational safety		Purchase/Market Value
	Health & Wellness Effect		Installation and Training Cost
	Ethical Responsibility		Opertaional Cost
	Scoial Impact		
Design for Functionality	Service Life/Durability		
	Modularity		
	Ease of Use		
	Maintainability		
	Serviceability		
	Upgradability		
	Ergonomics		
	Reliability		
	Functional Effectiveness		

On the other hand, according to Ljungberg, the life cycle of each product is largely defined by the extracting and processing raw materials, then the design, development and production, and use and disposal of materials [6]. Basically, the product life cycle can be evaluated in all four stages.

Gamberinia, Gebenninia, Manzini, Ziveria, argues that the R6 method addresses the three pillars of economics, environment, and society, and considers all four stages of the life cycle [7]; thus, proposing an integrated approach for developing sustainable products with a focus on design. His proposed integrated approach to sustainable product development is demonstrated in Fig. 2 and includes reducing, reuse, recycle, recover, redesign, and reproduction (remanufacturing).

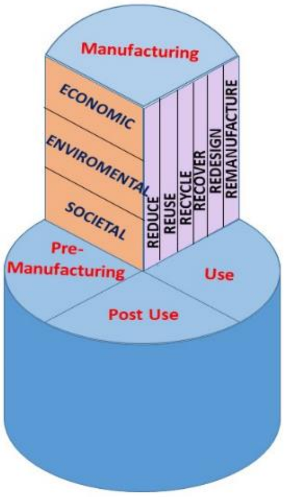

Fig. 2. The R6 structure in product life cycle stages (Budverden et al. 2009)

Hence, sustainable design and development aims to involve the social, economic, and environmental pillars in the design and development of the final product platform or products and to solve the existing problems of these aspects in the said process. This design method deals with aspects such as the effect of materials or energy on the manufacturing process, product use, and the ability to recycle the final product with minimal adverse impacts on the environment.

Different researchers each define different sub-components in terms of the three aspects of sustainability; however, the sub-components upon which they mainly agree are as follows: the economic sub-components include design and development costs, labor, energy, raw materials, equipment and revenue from recycling, the environmental sub-components consist energy consumption and CO2 emissions, and social sub-components is composed of recyclability, disassembly, and customer satisfaction with the quality and after-sales service.

Sustainability is defined as the ability of a product to function continuously with minimal environmental impact while providing economic and social benefits. Today, Jayal's views have determined approximately 80% of sustainability's effects on product development stages [4]. To address this issue, Moreover, Reap, Roman, Duncan & Bras claims that companies can basically identify environmental impacts on their products and processes by relying on product life cycle assessment and then directly reduce the negative impact [8]. Accordingly, Life Cycle Assessment (LCA) is a suitable method to evaluate the effects of a product as well as the resources used during the product life cycle and Ameli, Mansour, Ahmadi-Javid believed that the design and production of sustainable products is an important strategy [9]. On the other hand, Haber and Fargnoli believe that sustainable product design provides solutions to effectively deal with the functional attributes of the product balancing the three pillars of sustainability simultaneously since all three aspects of sustainability should be considered as an integral part of sustainable design [10].

Eckert, Wynn, Maier and Albers objectives and perspectives the models of the design and development process that have been published over the years represent different objectives and perspectives, and provide an organizational framework that clarifies the literature topology of these models and thus relates the main perspectives develop [11].

If life cycle assessment is viewed as a way to assess the significant environmental impacts as well as the impacts of resources used throughout a product's life cycle from raw material extraction to waste management, as Daddia, Nuccia and Iraldoab point out, it can be beneficial for product design, predicting life cycle effects and help determine if new environmental solutions are better than existing ones [12].

As mentioned in ISO 14040, 14041, 14042 and 14043 international standards and also based on the studies of Tao et al., product life cycle evaluation can bring many benefits to product design and foresee various life cycle effects [13]. However, it is believed that evaluating the life cycle of a product is especially complex, expensive, and time-consuming.

As a result, in recent years, sustainability has been promoted through the constant sharing of information at different stages of the product life cycle on product life cycle management software systems. In this process, product design and development knowledge is well maintained and leads to additional sustainability in the final product. In this approach, sustainability can be synonymous with optimizing the use of resources throughout the product life cycle while maintaining the quality of products and services.

In another study, Schöggla, Baumgartnera and Hoferb explored a wide range of different engineering methods to select the right materials in order to achieve a more sustainable product [14]. This study deals with the challenges and problems in designing products and production systems, which are due to the ever-changing customer needs, and increasing changes and frequent complexities of the product and resources required. Moreover, the present study claims that integrated design processes can lead to the integrated development of products and production systems .

Furthermore, Arabi and Gholamian in their research presented a three-objective multi-period multi-product mixed-integer quadratic programming problem to optimize a sustainable stone supply chain network design [15]. They believed that integrated design processes lead to the integrated development of products and sustainable manufacturing systems. Moreover, these researchers examined the relationship between the interactions of these design processes from a resource efficiency perspective presenting a new model of sustainable design. Additionally, they discussed the environmental advantages of shared products and manufacturing design systems.

Dahmani et. al. in their research discussed that the Lean design and Eco-design, associated with Industry 4.0 technologies, can be an efficient structured and methodological approach in developing products based on the circular economy strategies [16]. Indeed, decisions made during the product design stage can significantly impact the sustainability of products throughout their life cycle.

Setti, Canciglieri and Estorilio in their study analyzed a proposal of applying an iterative method for IPDP, based on established EV and DFA techniques, which seeks the balance between value and cost of all functions of a mechanical subset [17]. Thus, it was possible to evaluate the method application and analyze both its gains and its limitations.

Stanujkic, Popovic, Zavadskas, Karabasevic et. al. assessment of progress towards achieving sustainable development goals of the “Agenda 2030” by Using the CoCoSo and the Shannon Entropy Methods [18].

As can be seen in the review of the literature, many research and studies have been conducted on the development of sustainability in new products; however, none on the subject of revising the process of product design and development in a gateway system and reviewing and revising the most efficient deliverables in sustainable product development and ultimately, revising and developing new product attributes.

Finally, based on the studies conducted in the mentioned fields, until today, no study has been done to evaluate and select the most effective process group and the most effective deliverable in establishing sustainability and its pillars in the new product design and development process, and accordingly, the present study discusses this research gap.

Problem statement

Studies conducted on the current product design and development process indicate the fact that only a limited number of sustainability goals have been mentioned. However, due to the increasing development of sustainability and its valuable role in manufacturing new products, identifying new product development processes and selecting the most effective deliverables can be extremely crucial for establishing principles of sustainability and manufacture of sustainable products, which is the main idea of this article.

Given the breadth of product design and development process groups and their role in developing sustainability in various stages of the product life cycle, the primary purpose of this study is to rank and identify the most effective and efficient process groups in establishing sustainability in the product life cycle. Additionally, according to the research gap mentioned in the introduction, the next goal of this research is to identify the most important deliverables in the selected relevant process. In both objectives, the problem is analyzed and evaluated by relying on AHP techniques and the combined-compromise solution technique (COCOSO).

Problem solving steps

In this research, first, design process groups, new product development and the gates of each process group, deliverables, and the main criteria of sustainability are introduced. Subsequently, with the help of pairwise comparisons and using the opinions of automotive industry experts to determine weights the three criteria of sustainability are discussed. The new product design and development process groups are ranked using the AHP technique and the COCOSO technique (combined solution method); then, the most effective process group in product sustainability is selected. Afterwards, by employing pairwise comparisons and using the data collected from automotive industry experts, the weights of the four stages of the product life cycle are determined. Furthermore, by applying the AHP technique and COCOSO once more, 34 deliverable items are ranked based on the weights of the four stages of the life cycle, and eventually, the deliverable items promoting the most sustainability of the final product are selected.

Research method

The results of the present study can be used to provide a method for selecting the process group as well as deliverables with the greatest impact on sustainable product development in the automotive industry. This study is in the category of developmental research in terms of purpose and nature and uses survey research for data collection. It is also a descriptive-survey study based on the nature and method of data collection.

The research flow diagram is schematically presented in Fig. 3.

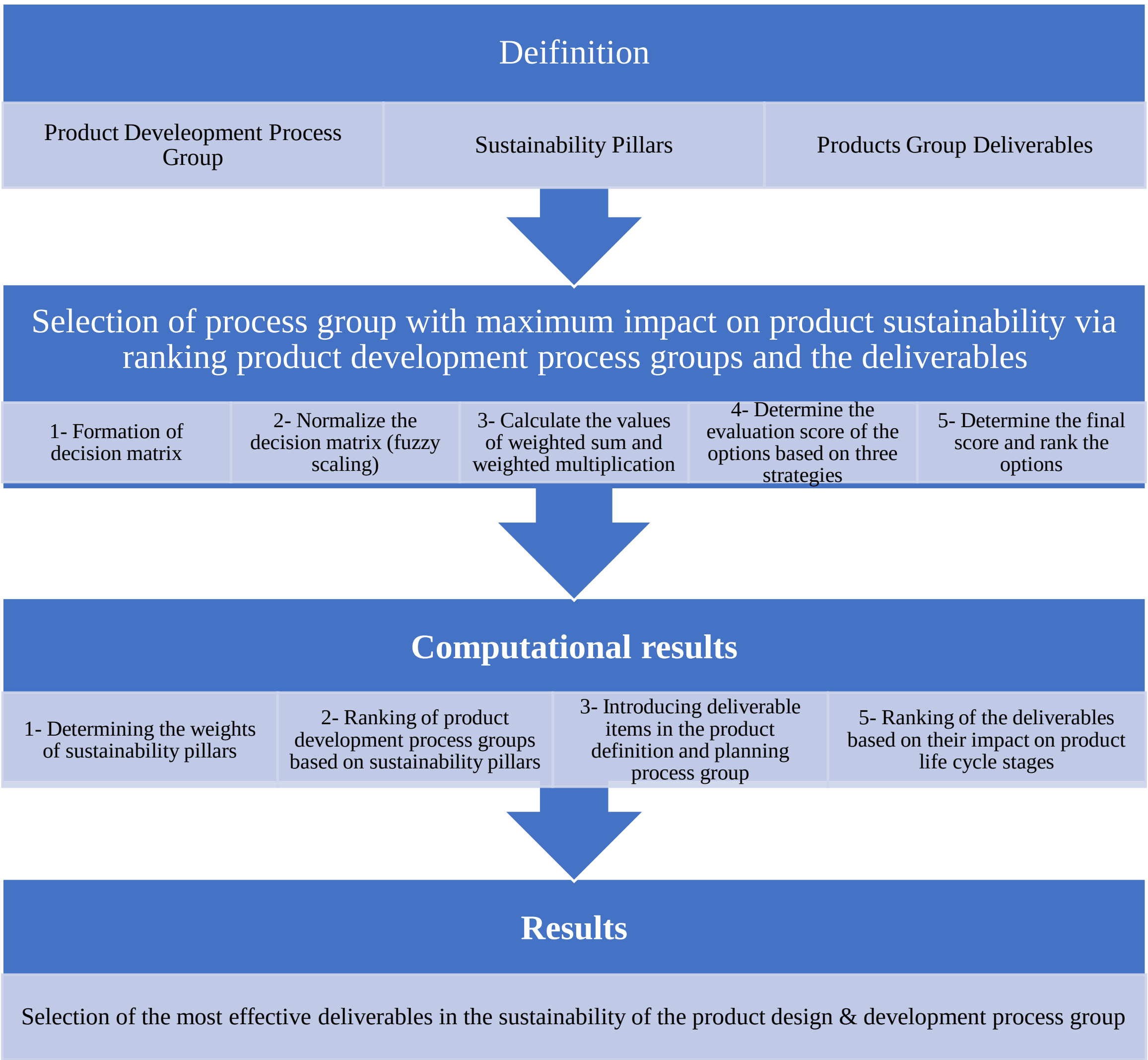

Fig. 3. Research flow diagram

This paper uses the Delphi technique for pairwise comparisons and the AHP technique for ranking the pillars of sustainability in four stages of the product life cycle. Then, the COCOSO technique is employed to rank and select the new product design and development process groups with the most impact on product sustainability and to rank 34 deliverables based on the weights of four stages of the life cycle. Finally, deliverable items with the greatest effect on promoting the sustainability of the final product are chosen.

Collection methods and tools

In order to collect data for the present study, two methods of library and field methods have been adopted.

Statistical population of research

The statistical population of this research is the managers and experts of new product research and development centers in automotive companies.

Data collection tools

A questionnaire was designed to collect the opinion of experts on the selection of the effective process groups in the development of product sustainability as well as deliverable items by introducing the main process groups of product development and the pillars and sub-pillars of sustainability in a product from three economic, environmental, and social perspectives.

Reliability and validity of research tools

Using SPSS software, Cronbach's alpha coefficient is obtained. For the new product development process groups questionnaire, Crunbach's alpha coefficient was 0.75, which indicates the high success rate of the questionnaire.

Data analysis method

For data analysis, AHP hierarchical analysis ranking method was used in addition to COCOSO i.e. combined compromise solution technique.

General characteristics of the respondents

Descriptive statistical indicators have been used to describe the general characteristics of the respondents. The education and work experience of respondents –experts- in product design and development centers are presented in Tables 2 and 3.

Table 2. Specifications of experts in the field of product design and development (Education level)

Education level	Number of experts	Percentage
Bachelor	4	50%
MA	3	37%
Ph.D	1	12%

Table 3. Specifications of experts in the field of product design and development (Work experince)

Work experience	Number of experts	Percentage
Under 10 years	0	0%
11 to 20 years	2	25%
25 to 30 years	6	75%

Ranking product development process groups and the deliverables

The goal at this stage is to identify the most effective and efficient process group in the set of four process groups of designing and manufacturing a new product in terms of promoting the final product sustainability. As mentioned previously, the four main process groups of new product design and production include product planning and definition, product design and development, process design and development, and product/process validation. Therefore, if the 4 processes described above are to be ranked based on the three main pillars of sustainability, meaning economic, environmental and social, the Delphi approach, expert opinion polls, the AHP group hierarchical analysis method, and the COCOSO technique are employed to weigh and determine the importance of criteria.

The COCOSO method is one of the relatively new multi-criteria decision-making techniques that was presented by Yazdani et al. in 2018. In this method, a combined compromise solution is provided for ranking options. The COCOSO method is one of the methods that only aims to rank research options and it is similar to methods such as TOPSIS, VICOR, and ELECTRIC.

These methods begin with the formation of the decision matrix and the weight of the criteria that was previously determined based on the group hierarchical analysis method is obtained as input.

The steps of the COCOSO technique described below are as follows, forming a decision matrix, normalizing the decision matrix, calculating the weighted sum and multiplication values, determining the evaluation score of the options based on the 3 strategies, and determining the final score and ranking of the options.

In this method, there is an integrated model of simple weighted sum (SAW) and weighted product method (WPM), the steps of which are provided below. Moreover, in the base article of this method, two terms WSM and WPM have been used to combine this method, in which WSM stands for weighted sum model and WPM stands for multiplication model.

Step 1: Form a decision matrix

In fact, the first step in all multi-criteria decision making methods is to form a decision matrix, which is given in the Eq. 1.

$$x_{ij} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ \vdots & & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}; \quad i = 1.2.\dots.m;\ j = 1,2,\dots,n \tag{1}$$

In this regard, x_{mn} is the evaluation of the *m* option based on the criterion *n*, which can be based on both verbal expressions and real, quantitative data. Verbal expressions can be based on a spectrum of 5 or 9.

Step 2: Normalize the decision matrix (fuzzy scaling)

Data normalization occurs in almost all multi-criteria decision-making methods. In this step, based on Eqs. 2 and 3, the decision to use the fuzzy normalization method becomes normal and Eq. 2 is used for positive criteria and Eq. 3 is used for negative criteria.

$$r_{ij} = \frac{x_{ij} - minx_{ij}}{maxx_{ij} - minx_{ij}};\ for\ benefit\ criterion \tag{2}$$

$$r_{ij} = \frac{\max x_{ij} - x_{ij}}{maxx_{ij} - minx_{ij}};\ for\ cost\ criterion \tag{3}$$

In the following equations, $max\ x_{ij}$ and $min\ x_{ij}$ are the maximum and minimum values of each benchmark column. Based on this normalization, all criteria are placed between 0 and 1.

Step 3: Calculate the values of weighted sum and weighted multiplication

In this step, the weighted sum (S) and weight multiplied (P) values for each option are calculated by applying Eqs. 4 and 5.

$$S_i = \sum_{j=1}^{n} (w_j r_{ij}). \tag{4}$$

$$P_i = \sum_{j=1}^{n} (r_{ij})^{w_j}. \tag{5}$$

In the mentioned equations, w_j is the weight of the criteria, which is entered as the input of the COCOSO method.

This weight can be calculated directly by the decision maker, individuals, or methods such as Shannon's entropy, AHP, BWM, and similar methods. S_i values are actually derived from the SAW method and P_i values are derived from the VASPAS technique.

Step 4: Determine the evaluation score of the options based on three strategies
In this step, option scores are obtained based on three strategies using Eqs. 6, 7, and 8.

$$k_{ia} = \frac{P_i + S_i}{\sum_{i=1}^{m}(P_i + S_i)} \tag{6}$$

$$k_{ib} = \frac{S_i}{\min_i S_i} + \frac{P_i}{\min_i P_i} \tag{7}$$

Eq. 6 states the arithmetic mean of the WSM and WPM scores, while Eq. 7 represents the relative scores of the WSM and WPM compared to the best. Eq. 8 is a compromise between the WSM and WPM models. In this equation, λ is determined by the decision-maker, but in case λ is equal to 0.5 and it might have a lot of flexibility.

$$k_{ic} = \frac{\lambda(S_i)+(1-\lambda)\,(P_i)}{\left(\lambda \max_i S_i+(1-\lambda)\max_i P_i\right)}\;; \quad 0 \le \lambda \le 1 \tag{8}$$

Step 5: Determine the final score and rank the options
In this step, the final score is calculated by employing Eq. 9. In fact, this equation represents the sum of the geometric mean and arithmetic mean of the three strategies from the previous stage. If an option has a higher score (k), it is indicated that this option is the superior one.

$$k_i = (k_{ia}k_{ib}k_{ic})^{\frac{1}{3}} + \frac{1}{3}(k_{ia} + k_{ib} + k_{ic}) \tag{9}$$

Computational results

Fig. 4 demonstrates the structure of target levels, criteria, and options in ranking of new product design and development process groups based on the sustainability pillars.

Determining the weights of sustainability pillars

As stated, in order to rank the pillars of sustainability, the necessary data was collected for analysis and selection of the best option with the cooperation of eight automotive industry experts in various fields and obtaining their opinions with the pairwise comparison questionnaire.

To convert these criteria into quantitative figures and fill in the pairwise comparison table, they were put on a scale from one to nine (AHP scale) as a means to determine the relative importance of each element compared to other elements in relation to that property. Table 4 exhibits the degree of importance after conducting pairwise comparisons.

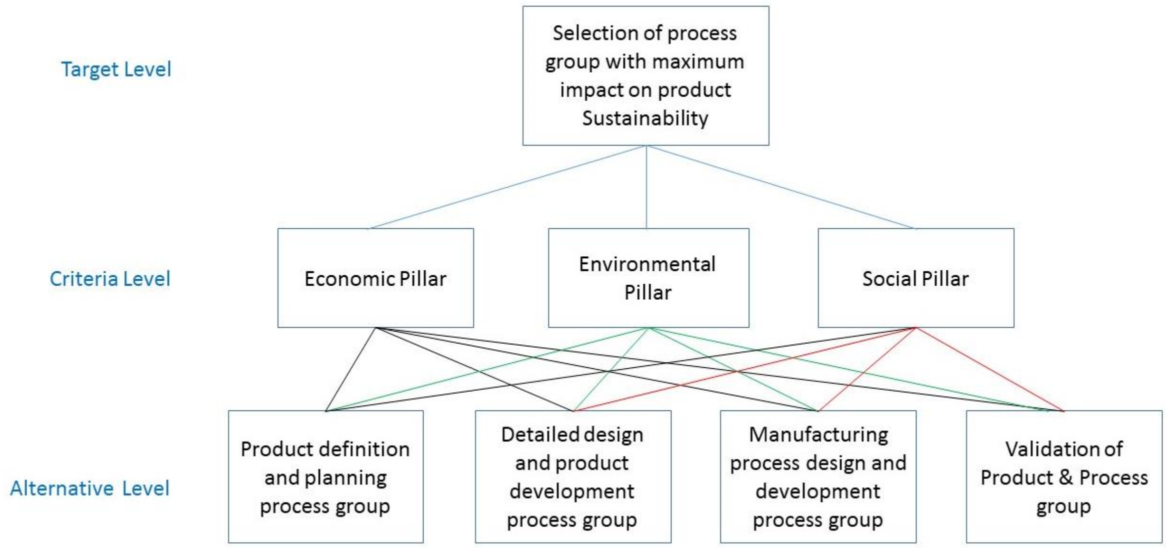

Fig. 4. Structure of target levels, criteria, and options in the ranking of product design and development process groups

Table 4. Table of degree of importance in pairwise comparisons

Description	The importance of the index	
The two elements are equally important	Equal importance	1
One element is relatively "preferred" over another.	Relatively preferred	3
One element is much preferred over another.	High preference	5
One element is much more preferred than the other.	High preference	7
One element has a huge preference over another.	Extremely high preference	9
	Intermediate values in judgments	2,4,6,8

Accordingly, the pairwise comparison table of sustainability pillars has been drawn with the cooperation of 8 experts in the automotive industry who are well acquainted with the issue of sustainability. The results are presented in Table 5.

Based on Eq. 10 and by summarizing the opinions of experts and obtaining the geometric mean of those opinions, the matrix of the pairwise comparisons mean is obtained as illustrated in Table 5.

$$x'_{ij} = \left(\prod_{l=1}^{8} x_{ijl} \right)^{1/8} \tag{10}$$

Table 5. Matrix of mean combined pairwise comparisons

	Economic Pillar	Enviromental Pillar	Social Pillar
Economic Pillar	2.195	1.223	1
Enviromental Pillar	2.956	1	0.818
Social Pillar	1	0.338	0.455
Sum.	6.151	2.561	2.273

After forming the matrix of pairwise comparisons for the criteria, we normalize its values and obtain the average of each row i.e. the weights of sustainability pillars, as shown in Table 6.

Table 6. Matrix of normalize mean combined pairwise comparisons

	Social Pillar	Enviromental Pillar	Economic Pillar	mean (relative weight)
Economic Pillar	0.439	0.477	0.357	**0.424**
Enviromental Pillar	0.359	0.390	0.480	**0.409**
Social Pillar	0.200	0.132	0.162	**0.164**

Ranking of product development process groups based on sustainability pillars

According to the findings of the study, the new product design and development mainly includes the following 4 processes:
G1: Product definition and planning process group
G2: Detailed design and product development process group
G3: Manufacturing process design and development process group
G4: Validation of Product and Process group

The combined compromise solution method (COCOSO) ranks the product development process groups. For this purpose, according to Tables 7, 8, and 9, by forming the decision matrix, the score of each option is determined for each criterion and then, with the help of the fuzzy normalization method, the decision matrix is formed.

Table 7. Experts' opinions on the impact of each process groups on the economic Pillar

	Economic Pillar								
expert	1	2	3	4	5	6	7	8	mean
G1	8	9	7	9	8	9	8	7	8.125
G2	7	8	6	5	8	7	6	5	6.5
G3	8	5	6	6	7	5	6	6	6.125
G4	4	3	2	1	3	5	4	3	3.125

The 9-point scale is applied here, number 1 being the very little impact, number 5 the medium impact, and number 9 the very high impact.

Table 8. Experts' opinions on the impact of each process groups on the environmental pillar

	Enviromental Pillar								
expert	1	2	3	4	5	6	7	8	mean
G1	9	9	7	9	9	9	8	8	8.5
G2	8	9	7	6	8	7	6	6	7.125
G3	7	8	5	7	6	6	7	7	6.625
G4	5	4	3	5	2	4	3	4	3.75

Table 9. Experts' opinions on the impact of each group of processes on the Social pillar

	Social Pillar								
expert	1	2	3	4	5	6	7	8	mean
G1	7	8	8	9	7	8	9	8	8
G2	8	9	7	7	8	8	7	7	7.625
G3	4	3	2	4	4	3	5	5	3.75
G4	3	3	4	3	4	4	5	5	3.875

The average opinions of experts is presented in Table 10 in order to determine the importance and impact of sustainability pillars on the product design and development process groups.

Table 10. Summary of the experts' opinions on the impact of each sustainability pillar on process groups

	Economic Pillar	Enviromental Pillar	Social Pillar
G1	8.125	8.5	8
G2	6.5	7.125	7.625
G3	6.125	6.625	3.75
G4	3.125	3.75	3.875

Based on the COCOSO method's second step, with the help of fuzzy normalization method, the normalized numbers are as displayed in Table 11.

Table 11. Experts' normalized opinions (Fuzzy Normalization) on the impact of sustainability Pillars on each process group

	Economic Pillar	Enviromental Pillar	Social Pillar
G1	1.000	1.000	1.000
G2	0.675	0.711	0.912
G3	0.600	0.605	0.000
G4	0.000	0.000	0.029

The values of weighted sum (S) and multiplied weight (P) are calculated in the next step for each option. The weight of the criteria, which was previously determined by the AHP method, has been included in the COCOSO method. The weights calculated for the economic, environmental, and social pillars are equal to 0.424, 0.409, and 0.164 respectively. The results of weighted sum S and weighted P obtained from Eqs. 6, 7, 8, and 9 and the score of options based on three strategies are presented in Table 12.

The first strategy (Kai) represents the arithmetic mean of WSM and WPM scores, while the second strategy (Kbi) represents the relative scores of WSM and WPM compared to the best, and the third strategy (Kci) represents a compromise between the models, WSM and WPM. In this regard, λ is determined by the decision-maker, but when λ is considered equal to 0.5, it causes a lot of flexibility.

Table 12. Results of weighted addition, weight multiplication and triple strategies

	S	P	Kai	Kbi	Kci
G1	0.997	3	0.395	212.044	1
G2	0.726	2.701	0.339	155.398	0.857
G3	0.502	1.62	0.21	106.951	0.531
G4	0.005	0.561	0.056	2	0.142

Finally, the final score and ranking of options is as demonstrated in Table 13.

Table 13. Results of final score and rank (Ki) of product development processes groups

Ki	Final Score
G1: Product definition and planning process group	75.523
G2: Detailed design and product development process group	55.759
G3: Manufacturing process design and development process group	38.181
G4: Validation of Product & Process group	0.984

Based on the final score, the product definition and planning process group is established as the most effective process group in ascertaining sustainability in the final product. Accordingly, the next step deals with the details and elements of this process group to identify the most important output and deliverables in terms of their respective impact on product sustainability in the product life cycle.

Introducing deliverable items in the product definition and planning process group

Considering the fact that the items delivered at each stage of the process are the best platform for establishing the principles of sustainability in that process, in this step, the deliverables in the product definition and planning process group are introduced.

Based on research conducted in the studied design and development companies, the deliverables in the process of product planning and definition include 33 items, which are as follows, Product requirements document, Feature list, Product design specification, Target book, Styling brief (exterior), Sketch, Renders, Theme selection (internal & external), Clinic and Styling Sign off, Supplier nomination list, System-Product design specification, 2/5 Physical model, Clinic and Styling sign off , Part status report, Design quality plan, Add and Delete List, Cost pack, 3D CAS modelling / Virtual model – C level, CAE/CFD analysis report (CAS Model), Vehicle architecture, Clinic and Styling Sign off (1:1 Physical), Ergonomic packaging layout model, Supplier selection, Digitize data, PSS- Appearance characteristics of parts, prototype / mule (1:1), Prototype / mule test report, Styling demand for gap and flashness, Section book, 3D CAS modelling / virtual model–B level, CAE/CFD analysis report, Digital mockup analysis report, Design verification plan, Features and structure of prototype manufacturing, kitting list (a bill of materials tracks the parts or components used to make an evaluation prototype).

Determining the impact of deliverables on establishing sustainability in life cycle stages

As previously stated, the main stages of a product life cycle include the following:

- Product design and development stage
- Manufacturing stage
- Use stage
- End of life stage

At this level, eight experts in the automotive industry were provided with a questionnaire to determine the importance of each of the four stages of the product life cycle in product sustainability. Since the evaluated indicators are qualitative, the bipolar distance method is applied. This measurement is based on an eleven-point scale with zero being the lowest and 10 being the highest value.

After forming the matrix of pairwise comparisons, we normalize its values and obtain the average of each row. Since the evaluated indicators are qualitative, the distance bipolar scale method is used. This measurement, as presented in Table 14, is based on an eleven-point scale in which zero is the lowest and 10 is the highest value. The normalized matrix Paired comparisons of indices and relative weights of product life cycle stages are presented in Table 15.

Table 14. Integrated pairwise comparison matrix of product life cycle stages

	S1 : Product design and development stage	S2 : Production stage	S3 : Use stage	S4 : Post Use Stage
S1 : Product design and development stage	1.000	6.086	5.281	3.936
S2 : Production stage	0.164	1.000	0.227	5.308
S3 : Use stage	0.189	4.414	1.000	6.074
S4 : Post Use Stage	0.254	0.188	0.165	1.000
Total	1.608	11.688	6.672	16.318

Table 15. Normalized matrix Paired comparisons of indices and relative weights of product life cycle stages

	S1 : Product design and development stage	S2 : Production stage	S3 : Use stage	S4 : Post Use Stage
S1 : Product design and development stage	0.2412	0.7915	0.5207	0.6220
S2 : Production stage	0.3722	0.1499	0.3776	0.1178
S3 : Use stage	0.3253	0.0340	0.0856	0.1022
S4 : Post Use Stage	0.0613	0.0247	0.0161	0.1580
Total	0.2412	0.7915	0.5207	0.6220

The calculated weights of product design and development, production, use, and post-use stages are equal to 0.5438, 0.2544, 0.1368, and 0.0650, respectively. In this step, in order to identify the most effective deliverables of the product definition and planning process group in the four stages of the product life cycle, the opinions of 8 automotive industry experts who are fully familiar with the deliverables of detailed design and product life cycle are used. In addition, their views on the impact of 39 deliverables in each of the four stages of the product life cycle (evaluation indicators) were obtained. Consequently, the four decision indicators include the following:

A1: Index of the impact of deliverables on establishing sustainability in the design and product development phase
A2: Index of the impact of deliverables on establishing sustainability in the production phase
A3: Index of the impact of deliverables on establishing sustainability in the use phase

A4: Index of the impact of deliverables on establishing sustainability at the end of the product life

Furthermore, the matrix of group pair comparisons was completed with a survey of experts and presented in Tables A.1-2 of Appendix B. By summarizing the survey of experts and obtaining the geometric mean of them (Formula No. 10), the main matrix is acquired as showcased in Table A.3 of Appendix B.

According to Table A.3, Appendix B, the weight of the index of the number of deliverables of the product planning and definition process group in establishing sustainability in the product design and development stage (A1) is equal to 0.543. The relative weight of the index of the impact of these deliverables on establishing sustainability in the production stage (A2) is equal to 0.254. The relative weight of the index of the impact of these deliverables on establishing sustainability in the use stage (A3) is equal to 0.136. Finally, the relative weight of the index of the impact of these deliverables on establishing sustainability at the end of the product life (A4) is equal to 0.065. At this stage, a questionnaire from experts to determine the importance of each deliverable item based on their impact on the product life cycle was prepared and provided to eight experts. The evaluated indicators used here are qualitative; therefore, the bipolar distance method is employed. This measurement, presented in Table 16, has an eleven-point scale basis with zero as the lowest and 10 as the highest value.

Table 19. Distance bipolar scale table

0	1	2	3	4	5	6	7	8	9	10
	Very Low		Low		Medium		high		Very high	

Ranking of the deliverables based on their impact on product life cycle stages

At this stage, the deliverable items of the product planning and definition process group are ranked and selected based on their impact on the four stages of the product life cycle. These items are ranked through the combined compromise solution method (COCOSO); hence, by forming the decision matrix, the score of each option for each of the criteria is acquired. Later, with the help of the fuzzy normalization method of the decision matrix takes.

Taking the number of experts participating in this study into account, the average score is calculated out of 8. The basis of this ranking is a 9-point scale, 1 as having very little effect, 5 as having medium effect, and 9 as having very high effect. The collected views of experts on the impact of each deliverable item on different stages of the product life cycle i.e. product design and development, production, use and post use are demonstrated in Tables A.4, 5, 6 and 7 of Appendix B.

Moreover, the geometric mean of the experts' opinions (x'_{ij}) is obtained and the main matrix is computed based on Eq. 10 and the summary of the experts' opinions as showcased in Table A.8 of Appendix B and the normalized experts' opinions on the impact of each deliverable on the all process group are presented in Table A.9 of Appendix B.

The normalized numbers are calculated through the fuzzy normalization method at the second step of the COCOSO method and are presented in Table 26.

Subsequently, the values of weighted sum (S) and weighted multiplication (P) are acquired for each option. At this stage, the weight of the criteria, which was previously determined by the AHP method has been inputted into the COCOSO method.

The weights calculated for the stages of product design and development, production, use, and post use are equal to 0.5438, 0.2544, 0.1368, and 0.0650, respectively.

The following are determined based on formulas 6, 7, 8 and 9, the weighted sum S and the weighted P and the score of the options based on 3 strategies, the first strategy (Kai) (arithmetic mean of WSM and WPM scores), the second strategy (Kbi) compared to The best, the relative scores of WSM and WPM and the third strategy (Kci) (compromised between WSM and WPM models) and finally the final score and ranking of options (Ki). In this regard, λ is set by the decision-maker at 0.5, which allows a great deal of flexibility.

Tabel 26. Normalized (fuzzy normalization) opinions of experts regarding the effect of each of the deliverables on the product life cycle stages and the Results of Weighting, Multiplication, and Triple Strategies and "Final Scoring and Option Ranking"

	Product design & development stage	Production stage	Use stage	Post Use Stage	S	P	Kai	Kbi	Kci	Ki		Product design & development stage	Production stage	Use stage	Post Use Stage	S	P	Kai	Kbi	Kci	Ki
Product Requirements Document	0.394	0.269	0.621	0.460	0.398	3.206	0.028	4.435	0.726	2.180	Vehicle Architecture	1.000	0.923	0.776	0.480	0.916	3.899	0.038	7.863	0.969	3.619
Feature List	0.424	0.346	0.707	0.560	0.452	3.307	0.03	4.813	0.757	2.343	Clinic & Styling Sign off (1:1	0.364	0.231	0.224	0.060	0.291	2.913	0.025	3.629	0.645	1.823
Product Design Specification	0.485	0.385	0.672	0.360	0.477	3.342	0.03	4.979	0.769	2.413	Ergonomic Packaging Layout	0.758	0.731	0.707	0.240	0.71	3.648	0.034	6.519	0.877	3.059
Target Book	0.970	1.000	1.000	1.000	0.984	3.983	0.039	8.306	1	3.803	Supplier Selection	0.515	0.500	0.724	0.380	0.531	3.431	0.031	5.349	0.798	2.571
Styling Brief (exterior)	0.394	0.231	0.672	0.360	0.388	3.174	0.028	4.36	0.717	2.147	Digitize Data	0.636	0.500	0.759	0.300	0.597	3.508	0.032	5.775	0.826	2.748
Sketch, Renders, Theme selection (internal & external)	0.727	0.731	0.879	0.760	0.751	3.729	0.035	6.807	0.902	3.183	PSS-Appearance characteristics of parts	0.394	0.077	0.586	0.100	0.32	2.914	0.026	3.797	0.651	1.890
Clinic & Styling Sign off	0.182	0.000	0.552	0.380	0.199	2.257	0.019	2.66	0.494	1.352	Prototype / Mule (1:1)	1.000	1.000	0.828	0.340	0.934	3.907	0.038	7.969	0.974	3.661
Supplier Nomination List	0.455	0.308	0.690	0.380	0.444	3.282	0.029	4.754	0.75	2.316	Prototype / Mule Test Report	0.758	0.462	0.776	0.100	0.642	3.508	0.033	6.035	0.836	2.850

	Product design & development stage	Production stage	Use stage	Post Use Stage	S	P	Kai	Kbi	Kci	Ki
System-Product Design	0.333	0.154	0.638	0.480	0.339	3.065	0.027	4.004	0.685	1.992
2/5 Physical Model	0.273	0.038	0.086	0.080	0.175	2.494	0.021	2.683	0.537	1.393
Clinic & Styling Sign off (2/5 Physical Model)	0.515	0.385	0.000	0.000	0.378	1.481	0.015	3.159	0.374	1.442
Part Status Report	0.727	0.615	0.845	0.560	0.704	3.665	0.035	6.495	0.88	3.052
Design Quality Plan	0.970	0.808	0.845	0.720	0.895	3.887	0.038	7.736	0.963	3.567
Add & \ Delete List	0.909	0.962	0.966	0.380	0.896	3.874	0.038	7.731	0.96	3.564
Cost Pack	0.939	1.000	0.983	0.400	0.926	3.906	0.038	7.924	0.973	3.643
3D CAS Modelling / Virtual Model	0.758	0.731	0.931	0.340	0.747	3.706	0.035	6.77	0.897	3.165
CAE/CFD Analysis Report (CAS	0.515	0.462	0.741	0.060	0.503	3.311	0.03	5.107	0.768	2.459

	Product design & development stage	Production stage	Use stage	Post Use Stage	S	P	Kai	Kbi	Kci	Ki
Styling Demand for Gap and Flashness	0.788	0.846	0.983	0.000	0.778	2.834	0.029	6.357	0.727	2.880
Section Book	0.394	0.423	0.759	0.080	0.431	3.217	0.029	4.632	0.735	2.260
3D CAS Modelling / Virtual Model	0.303	0.154	0.276	0.080	0.247	2.831	0.024	3.321	0.62	1.690
CAE/CFD Analysis Report	0.394	0.385	0.724	0.580	0.449	3.309	0.03	4.797	0.757	2.337
Digital Mockup Analysis Report	0.182	0.000	0.586	0.420	0.206	2.27	0.02	2.711	0.499	1.374
Design Verification Plan	0.909	0.923	0.948	0.200	0.872	3.823	0.037	7.56	0.945	3.490
Features and Structure of Prototype Manufacturi	0.000	0.577	0.672	0.520	0.273	2.775	0.024	3.43	0.614	1.726
Kitting List	0.697	0.615	0.690	0.540	0.665	3.617	0.034	6.239	0.862	2.945

Results and discussion

Based on the findings of the present research, the product planning and definition process group has earned the highest score (75,523) and has the ability to establish sustainability pillars with the highest effect on the development of a sustainable final product. Furthermore, a Target Book (third row) has been devised to list the deliverable items of the said process group, which has a final score of 3.803 with the highest impact on establishing sustainability in various stages of a product life cycle. Accordingly, the best way to implement sustainability requirements i.e. economic, environmental, and social pillars, in the product definition and design process group is to review and make the necessary changes to the Target Book.

Since this book contains all the objectives of the market, customers and government standards and plays a very important role in the design and development of the final product, so in the product planning process, however, this book should be compiled in more detail, The final product will be presented in greater compliance with market demands. Accordingly, this book can be a good tool for establishing sub-components of sustainability in its various parts to turn the final product into a product with sustainability features.

Conclusion and suggestions

Today, with the raising awareness of the economic, social and environmental impacts of products, the development of sustainable products is gaining more and more attention. Currently, the automotive industry is one of the most important industries in the world. Therefore, manufacturers are aiming to produce automobiles with minimal environmental impact, reduced cost, and socially appropriate effectiveness. The present article made an attempt to address the issues arising from the main processes related to establishing sustainability in the automotive industry. Given the breadth and complexity of the processes and the product development process reference model, the application of sustainability pillars in product design and development process groups requires sub-processes modification as well as the inclusion of sustainability pillars effects in the deliverables at each stage of the product life cycle.

Accordingly, the implementation of sustainability sub-pillars is comprised of the economic aspect including reducing labor costs, energy, materials, equipment, design and increasing revenue from recycling, the environmental aspect including reducing energy consumption, reducing $CO2$ pollution, and the social aspect including increasing recyclability, after-sales service, assembly capability, safety and customer satisfaction. The respective deliverables are presented as well. Furthermore, if through the same approach, the sustainability pillars are implemented in all related deliverable items in the product definition and planning process group, as well as applying the same pattern in the other product design and development process groups, then companies can move towards sustainable product design and development.

References

[1] Waage, A. (2007), Re-considering product design: a practical “road-map” for integration of sustainability issues, Journal of Cleaner Production, Volume 15, Issue 7, 2007, Pages 638-649

[2] Badurdeen, F., Iyengar, Deepak., Goldsby, Thomas J., Metta, Haritha., Gupta, Sonal., and Jawahirm I.S.,(2006). Extending total life-cycle thinking to sustainable supply chain design, International Journal of Product Lifecycle Management, Vol. 4, No. 1-3

[3] Azapagic,A., Millington, A., Collett, A.,(2006). A Methodology for Integrating Sustainability Considerations into Process Design, Chemical Engineering Research and Design, Volume 84, Issue 6, June 2006, Pages 439-452

[4] Jayal, A.D., Badurdeen, F., Dillon, O.W., Jawahir, I.S., (2010). Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels, CIRP Journal of Manufacturing Science and Technology, Volume 2, Issue 3, Pages 144-152

[5] Jawahir, I.S., (2008), Beyond the 3R’s: 6R Concepts for Next Generation Manufacturing: Recent Trends and Case Studies, Symposium on Sustainability and Product Development IIT, Chicago, August 7-8

[6] Ljungberg, L.Y., (2007). Materials selection and design for development of sustainable products, Materials & Design, Volume 28, Issue 2, Pages 466-479
[7] Gamberinia R., Gebenninia, E., Manzini, R., Ziveria, A., (2010). On the integration of planning and environmental impact assessment for a WEEE transportation network—A case study, Resources, Conservation and Recycling, Volume 54, Issue 11, September, Pages 937-951
[8] Reap, J., Roman, F., Duncan, S., & Bras, B. (2008), A survey of unresolved problems in life cycle assessment, The International Journal of Life Cycle Assessment volume 13, Article number: 374
[9] Ameli, M., Mansour, S., Ahmadi-Javid, A,. (2016). A multi-objective model for selecting de- sign alternatives and end-of-life options under uncertainty: A sustainable approach., Resources, Conservation and Recycling, 109. pp. 123-136.
[10] Haber, N. and Fargnoli. M., (2017). Design for product-service systems: a procedure to enhance functional integration of product-service offerings, International Journal of Product DevelopmentVol. 22, No. 2
[11] Eckert, C.M., Wynn, D.C., Maier, J.F., Albers, A. (2017). On the integration of product and process models in engineering design, Design Science , Volume 3
[12] Daddia, T., Nuccia. B., Iraldoab. F., (2017). Using Life Cycle Assessment (LCA) to measure the environmental benefits of industrial symbiosis in an industrial cluster of SMEs, Journal of Cleaner Production, Volume 147, 20 March, Pages 157-164
[13] Tao et al. (2017), J., Chen, Z., Yu, S., Liu, Z., 2017. Integration of Life Cycle Assessment with computer-aided product development by a feature-based approach. J. Clean. Prod. 143, 1144e1164
[14] Schöggla, J.P., Baumgartnera, R., Hoferb, D., (2017). Improving sustainability performance in early phases of product design: A checklist for sustainable product development tested in the automotive industry, Journal of Cleaner Production, Volume 140, Part 3, Pages 1602-1617
[15] Arabi, M., Gholamian, M.R., (2021). Sustainable Supply Chain Network Design with Price Based Demand Considering Sound and Dust Pollutions: A Case Study, Advances in Industrial Engineering, summer 2021, 55(3): 285-306
[16] Dahmani,N. et al., (2021). Smart circular product design strategies towards eco-effective production systems: A lean eco-design industry 4.0 framework, Journal of Cleaner Production, Volume 320
[17] Setti, P., Canciglieri, Jounior O., Estorilio, A. (2021). Integrated product development method based on Value Engineering and design for assembly concepts, Journal of Industrial Information Integration, Volume 21
[18] Stanujkic, D., Popovic, G., Zavadskas, E.K., Karabasevic, D., Binkyte, A., (2020). Assessment of Progress towards Achieving Sustainable Development Goals of the “Agenda 2030” by Using the CoCoSo and the Shannon Entropy Methods: The Case of the EU Countries, Sustainability, 12(14), 5717.

Appendix A - Biographical notes

Dr. Ali Bozorgi-Amiri received his B.Sc., M.Sc. and Ph.D. degrees in Industrial Engineering from Iran University of Science and Technology in Tehran, Iran. He is currently an Associate Professor in School of Industrial Engineering at University of Tehran. His research interests include Business process redesign, Operations management, Supply chain resilience, Humanitarian logistics, Data-Driven Decision Making. He has published several papers in related filed in refereed journals and conferences. In addition to being an associate professor at the Faculty of Industrial Engineering, University of Tehran, he is managing the University of Tehran Large Education Center and has so far concluded very important training contracts.

Mr. Davood Omidzadeh received his B.Sc. in Industrial Engineering from Malek Ashtar University and M.Sc. Degrees in Industrial Management from University of Tehran in Tehran, Iran. He is currently a Ph.D candidate at Islamic Azad University Science and Research Branch. His research interests include Product Design and Development, artificial intelligence neural network, Industrial Automation, Product Lifecycle Management, PDM in Design center, Automotive Industries Research and development and Data-Driven Decision Making. He has published several papers in related filed in refereed journals and he has also authored two books on concurrent engineering and the application of artificial intelligence to the accreditation of financial institutions.

Dr. Seyed Mojtaba Sajadi holds a Ph.D. in Industrial Engineering and Systems Management from Amirkabir University of Technology, Tehran, Iran. He received his MSc and BSc in Industrial Engineering from University of Tehran and Sharif University of Technology, respectively. His research interests include Data Science, Simulation-Based Optimization, Mathematical Modelling, Artificial Intelligence, and Machine Learning. He applies these research methodologies in Supply Chain, Health Care, Production Control, Disaster Management, Truism and Entrepreneurship. In 2015 he was selected as a young researcher in the fourth festival of the University of Tehran and his other executive responsibilities include the director of the library and computer center of the Faculty of Entrepreneurship.

Dr. Farzad Movahedi Sobhani received his PhD in Industrial Engineering from Department of Industrial and Systems Engineering, Tarbiat Modares University, Tehran, Iran. He is a faculty member at Islamic Azad University Science and Research Branch Tehran, Iran. His research area is business process management, knowledge management, statistical learning, and system dynamics. He has also led various projects at doctoral levels and has done several projects in the field of modeling with the help of system dynamics. His latest paper on electricity demand forecasting using a hybrid technique based on artificial intelligence neural network after propagation, wavelet transform and adaptive differential evolution algorithm.

Appendix B: Tables

Table A.1. Experts' opinions on the matrix of group pair comparisons

Paired comparisons of criteria - Expert No. 2						Paired comparisons of criteria - Expert No. 1				
	A1	**A2**	**A3**	**A4**			**A1**	**A2**	**A3**	**A4**
A1	1	7	4	3		**A1**	1	4	4	3
A2	0.14	1	0.25	5		**A2**	0.25	1	0.2	2
A3	0.25	4	1	6		**A3**	0.25	5	1	4
A4	0.33	0.2	0.16	1		**A4**	0.33	0.5	0.25	1
Paired comparisons of criteria - Expert No. 4						Paired comparisons of criteria - Expert No. 3				
	A1	**A2**	**A3**	**A4**			**A1**	**A2**	**A3**	**A4**
A1	1	5	6	4		**A1**	1	3	4	3
A2	0.2	1	0.2	5		**A2**	0.33	1	0.33	2
A3	0.16	5	1	3		**A3**	0.25	3	1	4
A4	0.25	0.2	0.33	1		**A4**	0.33	0.5	0.25	1
Paired comparisons of criteria - Expert No. 6						Paired comparisons of criteria - Expert No. 5				
	A1	**A2**	**A3**	**A4**			**A1**	**A2**	**A3**	**A4**
A1	1	7	4	4		**A1**	1	3	4	4
A2	0.14	1	0.25	6		**A2**	0.33	1	0.25	5
A3	0.25	4	1	5		**A3**	0.25	4	1	5
A4	0.25	0.16	0.2	1		**A4**	0.25	0.2	0.2	1
Paired comparisons of criteria - Expert No. 8						Paired comparisons of criteria - Expert No. 7				
	A1	**A2**	**A3**	**A4**			**A1**	**A2**	**A3**	**A4**
A1	1	5	4	5		**A1**	1	6	4	3
A2	0.2	1	0.33	0.2		**A2**	0.16	1	0.25	5
A3	0.25	3	1	1		**A3**	0.25	4	1	4
A4	0.2	4	1	1		**A4**	0.33	0.2	0.25	1

Table A.2. Integrated pairwise comparison matrix

	A1	A2	A3	A4
A1	1	6.086	5.281	3.936
A2	0.164	1	0.227	5.308
A3	0.189	4.414	1	6.074
A4	0.254	0.188	0.165	1
Total	1.608	11.688	6.672	16.318

Table A.3. Normalized matrix of pairwise comparisons of indices and relative weights

	A1	A2	A3	A4	Mean
A1	0.622	0.5207	0.7915	0.2412	0.5438
A2	0.1178	0.3776	0.1499	0.3722	0.2544
A3	0.1022	0.0856	0.034	0.3253	0.1368
A4	0.158	0.0161	0.0247	0.0613	0.065

Table A.4. Experts' opinions on the impact of each deliverables on the Design and Development process group

Design and Development Process									
	Expert 1	Expert 2	Exper t3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Mean
Product Requirements Document	8	7	7	6	6	8	7	7	7
Feature List	7	8	7	6	7	6	8	8	7.125
Project PDS	7	8	8	7	8	7	7	7	7.375
Target Book	10	9	9	10	8	10	9	10	9.375
Styling Brief (exterior)	7	7	8	6	8	7	7	6	7
Sketch, Renders, theme selection (internal & external)	8	7	9	8	9	9	8	9	8.375
Clinic & Styling Sign off	6	7	6	5	6	6	6	7	6.125
Supplier Nomination List	7	7	7	6	8	8	8	7	7.25
System PDS	6	7	6	7	7	7	7	7	6.75
2/5 Physical Model	6	7	7	6	6	7	6	7	6.5
Clinic & Styling Sign off (2/5 Physical Model)	7	8	7	8	7	7	8	8	7.5
Part Status Report	9	7	9	8	9	8	9	8	8.375
Design Quality Plan	9	9	9	10	8	10	10	10	9.375
Add & Delete List	10	9	9	10	9	9	8	9	9.125
Cost Pack	10	9	9	9	9	10	9	9	9.25
CAS / Virtual Model	9	8	9	9	8	8	8	9	8.5

Table A.4. Experts' opinions on the impact of each deliverables on the Design and Development process group

Design and Development Process									
	Expert 1	Expert 2	Exper t3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Mean
CAE/CFD Analysis Report (CAS Model)	7	8	7	8	7	7	8	8	7.5
Vehicle Architecture	9	10	9	9	10	9	10	10	9.5
Clinic & Styling Sign off (1:1 Physical Model)	7	6	5	7	8	7	8	7	6.875
Ergonomic Packaging Layout	8	9	9	9	9	8	8	8	8.5
Supplier Selection	7	7	8	8	7	8	7	8	7.5
Digitize Data	8	8	8	8	8	8	8	8	8
PSS	7	7	7	7	7	7	7	7	7
Prototype / Mule	10	10	10	9	9	10	9	9	9.5
Prototype / Mule Test Report	9	9	8	8	9	9	8	8	8.5
Styling Demand	8	8	8	9	9	9	9	9	8.625
Section Book	7	7	7	7	7	7	7	7	7
CAS / Virtual Model	7	7	7	7	6	7	6	6	6.625
CAE/CFD Analysis Report (Phase F)	7	7	7	7	7	7	7	7	7
DMU Analysis Report (Phase F)	6	6	6	6	7	6	6	6	6.125
DVP	9	9	9	9	10	9	9	9	9.125
PBC	5	5	7	5	6	5	5	5	5.375
Kitting List	8	8	9	8	8	8	9	8	8.25

Table A.5. Experts' opinions on the impact of each deliverables on the Production process group

Production									
	Expert 1	Expert 2	Exper t3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Mean
Product Requirements Document	7	6	6	6	5	7	6	6	6.125
Feature List	6	7	6	7	6	5	7	7	6.375
Project PDS	6	7	8	6	7	6	6	6	6.5
Target Book	9	8	9	9	7	9	8	9	8.5
Styling Brief (exterior)	6	6	6	5	7	7	6	5	6
Sketch, Renders, theme selection	7	7	8	7	8	9	7	8	7.625

Table A.5. Experts' opinions on the impact of each deliverables on the Production process group

Production									
	Expert 1	Expert 2	Exper t3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Mean
(internal & external)									
Clinic & Styling Sign off	5	6	5	4	6	5	5	6	5.25
Supplier Nomination List	6	6	7	5	6	7	7	6	6.25
System PDS	5	5	5	5	7	6	7	6	5.75
2/5 Physical Model	5	6	5	5	5	6	5	6	5.375
Clinic & Styling Sign off (2/5 Physical Model)	6	7	6	7	6	6	7	7	6.5
Part Status Report	8	6	7	7	7	8	7	8	7.25
Design Quality Plan	7	8	8	8	9	8	8	7	7.875
Add & Delete List	9	9	8	9	9	8	7	8	8.375
Cost Pack	9	8	9	8	9	9	8	8	8.5
CAS / Virtual Model	7	7	9	8	8	7	7	8	7.625
CAE/CFD Analysis Report (CAS Model)	7	7	6	7	7	6	7	7	6.75
Vehicle Architecture	8	8	7	9	9	8	8	9	8.25
Clinic & Styling Sign off (1:1 Physical Model)	5	5	4	6	7	8	7	6	6
Ergonomic Packaging Layout	7	8	8	8	8	8	7	7	7.625
Supplier Selection	7	6	8	8	6	7	6	7	6.875
Digitize Data	8	7	7	6	7	6	7	7	6.875
PSS	6	5	5	6	5	6	5	6	5.5
Prototype / Mule	9	8	8	9	9	9	8	8	8.5
Prototype / Mule Test Report	8	7	7	6	7	6	6	7	6.75
Styling Demand	7	9	7	9	8	8	8	8	8

Table A.5. Experts' opinions on the impact of each deliverables on the Production process group

Production									
	Expert 1	Expert 2	Exper t3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Mean
Section Book	6	7	6	7	7	6	7	7	6.625
CAS / Virtual Model	6	7	6	6	4	6	5	6	5.75
CAE/CFD Analysis Report (Phase F)	6	7	6	7	6	8	6	6	6.5
DMU Analysis Report (Phase F)	6	5	6	5	6	4	5	5	5.25
DVP	9	8	8	8	8	8	8	9	8.25
PBC	8	7	6	7	7	8	7	7	7.125
Kitting List	7	7	8	7	7	7	8	7	7.25

Table A.6. Experts' opinions on the impact of each deliverables on the Use process group

Use									
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Mean
Product Requirements Document	5	5	4	5	4	6	5	5	4.875
Feature List	5	6	5	6	5	5	6	6	5.5
Project PDS	5	4	7	5	6	5	5	5	5.25
Target Book	8	7	8	8	6	9	7	8	7.625
Styling Brief (exterior)	5	6	5	5	6	6	5	4	5.25
Sketch, Renders, theme selection (internal & external)	6	7	7	6	7	8	6	7	6.75
Clinic & Styling Sign off	5	5	4	3	5	4	4	5	4.375
Supplier Nomination List	5	6	6	5	5	5	6	5	5.375
System PDS	4	5	4	5	6	5	6	5	5
2/5 Physical Model	1	2	2	2	1	0	0	0	1
Clinic & Styling Sign off (2/5 Physical Model)	0	1	1	0	0	0	0	1	0.375
Part Status Report	7	5	7	6	7	7	6	7	6.5
Design Quality Plan	6	7	7	7	6	7	6	6	6.5

Table A.6. Experts' opinions on the impact of each deliverables on the Use process group

Use									
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Mean
Add & Delete List	8	8	7	8	8	7	6	7	7.375
Cost Pack	8	7	8	7	8	8	7	7	7.5
CAS / Virtual Model	8	8	8	7	7	6	6	7	7.125
CAE/CFD Analysis Report (CAS Model)	6	6	5	6	6	5	6	6	5.75
Vehicle Architecture	7	6	5	5	6	6	7	6	6
Clinic & Styling Sign off (1:1 Physical Model)	1	2	3	3	2	2	3	0	2
Ergonomic Packaging Layout	5	7	5	7	5	6	5	4	5.5
Supplier Selection	6	5	6	6	5	6	5	6	5.625
Digitize Data	7	6	6	5	6	5	6	6	5.875
PSS	5	4	4	6	4	5	4	5	4.625
Prototype / Mule	8	4	7	5	6	7	7	7	6.375
Prototype / Mule Test Report	7	6	6	5	6	5	5	8	6
Styling Demand	6	8	8	8	8	7	8	7	7.5
Section Book	5	6	6	6	7	6	5	6	5.875
CAS / Virtual Model	3	3	2	1	3	3	2	2	2.375
CAE/CFD Analysis Report (Phase F)	5	6	5	6	6	7	5	5	5.625
DMU Analysis Report (Phase F)	5	4	5	4	5	5	5	4	4.625
DVP	8	7	7	7	7	7	7	8	7.25
PBC	5	6	5	4	6	4	6	6	5.25
Kitting List	6	4	5	6	5	6	5	6	5.375

Table A.7. Experts' opinions on the impact of each deliverables on the After use process group

After use									
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Mean
Product Requirements Document	3	3	2	3	2	4	3	3	2.875
Feature List	3	4	3	4	3	3	4	4	3.5

Table A.7. Experts' opinions on the impact of each deliverables on the After use process group

After use									
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Mean
Project PDS	2	1	4	2	3	2	2	2	2.25
Target Book	6	7	6	6	7	7	5	6	6.25
Styling Brief (exterior)	2	3	2	2	3	3	2	1	2.25
Sketch, Renders, theme selection (internal & external)	4	5	5	4	5	6	4	5	4.75
Clinic & Styling Sign off	3	3	2	1	3	2	2	3	2.375
Supplier Nomination List	2	3	3	2	2	2	3	2	2.375
System PDS	2	3	2	3	4	3	4	3	3
2/5 Physical Model	1	0	0	0	1	1	0	1	0.5
Clinic & Styling Sign off (2/5 Physical Model)	0	0	0	0	0	0	0	0	0
Part Status Report	4	2	4	3	4	4	3	4	3.5
Design Quality Plan	4	5	5	5	4	5	4	4	4.5
Add & Delete List	3	3	2	3	3	2	1	2	2.375
Cost Pack	3	2	3	2	3	3	2	2	2.5
CAS / Virtual Model	3	3	3	2	2	1	1	2	2.125
CAE/CFD Analysis Report (CAS Model)	1	1	0	0	1	0	0	0	0.375
Vehicle Architecture	4	3	2	2	3	3	4	3	3
Clinic & Styling Sign off (1:1 Physical Model)	0	0	1	1	0	0	1	0	0.375
Ergonomic Packaging Layout	1	3	1	3	1	2	1	0	1.5
Supplier Selection	3	2	2	2	2	3	2	3	2.375
Digitize Data	3	2	2	1	2	1	2	2	1.875
PSS	1	0	0	2	0	1	0	1	0.625
Prototype / Mule	2	0	3	1	2	3	3	3	2.125
Prototype / Mule Test Report	1	0	0	1	0	1	1	1	0.625
Styling Demand	0	0	0	0	0	0	0	0	0
Section Book	1	1	0	0	1	0	0	1	0.5
CAS / Virtual Model	1	1	0	0	1	1	0	0	0.5
CAE/CFD Analysis Report (Phase F)	3	4	3	4	4	5	3	3	3.625
DMU Analysis Report (Phase F)	3	2	3	2	3	3	3	2	2.625
DVP	2	1	1	1	1	1	1	2	1.25
PBC	3	4	3	2	4	2	4	4	3.25
Kitting List	4	2	3	4	3	4	3	4	3.375

Table A.8. The mean experts' opinions on the impact of each deliverables on the all process group

	Design and Development Process	Production	Use	After Use
Product Requirements Document	7	6.125	4.875	2.875
Feature List	7.125	63275	5.5	3.5
Project PDS	7.375	6.5	5.25	2.25
Target Book	9.375	8.5	7.625	6.25
Styling Brief (exterior)	7	6	5.25	2.25
Sketch, Renders, theme selection (internal & external)	8.375	7.625	6.75	4.75
Clinic & Styling Sign off	6.125	5.25	4.375	2.375
Supplier Nomination List	7.25	6.25	5.375	2.375
System PDS	6.75	5.75	5	3
2/5 Physical Model	6.5	5.375	1	0.5
Clinic & Styling Sign off (2/5 Physical Model)	7.5	6.5	0.375	0
Part Status Report	8.375	7.25	6.5	3.5
Design Quality Plan	9.375	7.875	6.5	4.5
Add & Delete List	9.125	8.375	7.375	2.375
Cost Pack	9.25	8.5	7.5	2.5
CAS / Virtual Model	8.5	7.625	7.125	2.125
CAE/CFD Analysis Report (CAS Model)	7.5	6.75	5.75	0.375
Vehicle Architecture	9.5	8.25	6	3
Clinic & Styling Sign off (1:1 Physical Model)	6.875	6	2	0.375
Ergonomic Packaging Layout	8.5	7.625	5.5	1.5
Supplier Selection	7.5	6.875	5.625	2.375
Digitize Data	8	6.875	5.875	1.875
PSS	7	5.5	4.625	0.625
Prototype / Mule	9.5	8.5	6.375	2.125
Prototype / Mule Test Report	8.5	6.75	6	0.625
Styling Demand	8.625	8	7.5	0
Section Book	7	6.625	5.875	0.5
CAS / Virtual Model	6.625	5.75	2.375	0.5
CAE/CFD Analysis Report (Phase F)	7	6.5	5.625	3.625
DMU Analysis Report (Phase F)	6.125	5.25	4.625	2.625
DVP	9.125	8.25	7.25	1.25
PBC	5.375	7.125	5.25	3.25
Kitting List	8.25	7.25	5.375	3.375

Table A.9. The normalized experts' opinions on the impact of each deliverables on the all process group

	Design and Development Process	Production	Use	After Use
	0.5438	**0.2544**	**0.1368**	**0.0650**
Product Requirements Document	0.394	0.269	0.621	0.460
Feature List	0.424	0.346	0.707	0.560
Project PDS	0.485	0.385	0.672	0.360
Target Book	0.970	1.000	1.000	1.000
Styling Brief (exterior)	0.394	0.231	0.672	0.360
Sketch, Renders, theme selection (internal & external)	0.727	0.731	0.879	0.760
Clinic & Styling Sign off	0.182	0.000	0.552	0.380
Supplier Nomination List	0.455	0.308	0.690	0.380
System PDS	0.333	0.154	0.638	0.480
2/5 Physical Model	0.273	0.038	0.086	0.080
Clinic & Styling Sign off (2/5 Physical Model)	0.515	0.385	0.000	0.000
Part Status Report	0.727	0.615	0.845	0.560
Design Quality Plan	0.970	0.808	0.845	0.720
Add & Delete List	0.909	0.962	0.966	0.380
Cost Pack	0.939	1.000	0.983	0.400
CAS / Virtual Model	0.758	0.731	0.931	0.340
CAE/CFD Analysis Report (CAS Model)	0.515	0.462	0.741	0.060
Vehicle Architecture	1.000	0.923	0.776	0.480
Clinic & Styling Sign off (1:1 Physical Model)	0.364	0.231	0.224	0.060
Ergonomic Packaging Layout	0.758	0.731	0.707	0.240
Supplier Selection	0.515	0.500	0.724	0.380
Digitize Data	0.636	0.500	0.759	0.300
PSS	0.394	0.077	0.586	0.100
Prototype / Mule	1.000	1.000	0.828	0.340
Prototype / Mule Test Report	0.758	0.462	0.776	0.100
Styling Demand	0.788	0.846	0.983	0.000
Section Book	0.394	0.423	0.759	0.080
CAS / Virtual Model	0.303	0.154	0.276	0.080
CAE/CFD Analysis Report (Phase F)	0.394	0.385	0.724	0.580
DMU Analysis Report (Phase F)	0.182	0.000	0.586	0.420
DVP	0.909	0.923	0.948	0.200
PBC	0.000	0.577	0.672	0.520
Kitting List	0.697	0.615	0.690	0.540