D2.1 – List of Requirements and Functions

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Abstract

The present deliverable focuses on the collection of requirements and functions for the conceptual design phase at the example of an A-pillar design demonstrator from the automotive sector, as described in WP#2 of Fun4Design Project. WP#2 belongs to Design and Development phase which contributes to enhance the sustainability in automotive sector through the use of multi-functional materials. Specifically, this report focuses on: a) Defining the technical requirements of the a-pillar, (b) Identifying the primary functions and characterize them to enable a sustainable performance and (c) Creating the main simulations for future desktop studies. The present report also demonstrates that choosing a sustainable a-pillar structure necessitates balancing various factors including performance, environmental, economic, social impact, and circular economy considerations.

Keywords: Conceptual design, Sustainability, A-pillar, Automotive, Requirements, Functions

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1 INTRODUCTION

Deliverable D2.1, titled "List of Requirements and Functions", as part of the WP#2 of the Fun4Design project, aims to present the definition of the requirements and the functions that will be used as input to the conceptual sustainable design of the A-pillar automotive structure. Requirements and functions are essential in the conceptual design of a mechanical system as they define its scope, objectives, and constraints. Functions describe what the mechanical system fulfils, while requirements are derived from the stakeholder needs and express unambiguous targets the mechanical system shall achieve. Combined with the sustainability design methodology, the definition of requirements and functions assists in identifying trade-offs of suitable design variants during the early stages of conceptual design as presented in **Figure 1**. This systematic approach also leads to better design decisions and a more streamlined development process [1].

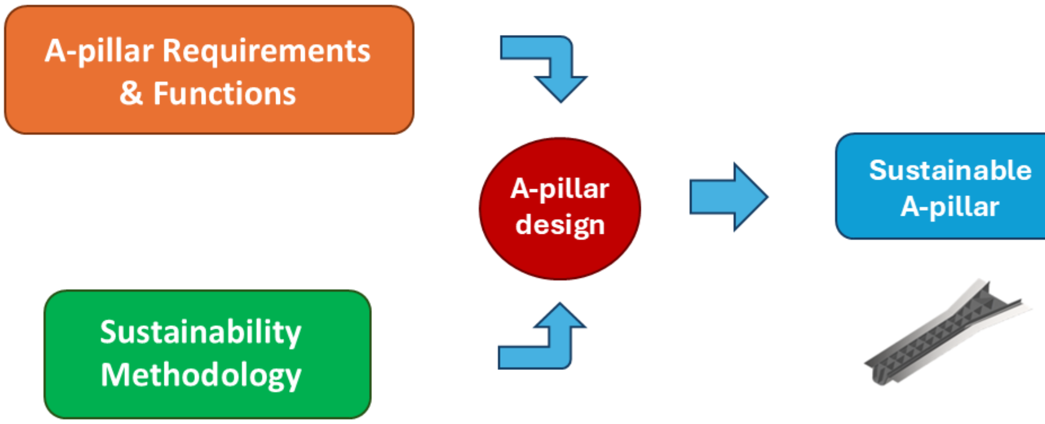

Figure 1: The combination of design requirements and functions and the sustainability methodology for the sustainable A-pillar design.

The A-pillar structure is a critical part of the automotive structure that supports the frame of a car and ensures the integrity of the passenger compartment. This structure has been selected to demonstrate the sustainable design methodology due to its high variability of design parameters, material composition, complex geometries, and loading conditions, which lead to a high effort for design case studies and simulations. The scope of this deliverable aligns closely with Task 2.2 of Work Package #2 (WP#2), which focuses on the representative A-pillar geometries at the component level using typical metallic and composite materials.

This deliverable starts with a description of the holistic character of sustainability and the current sustainability efforts in the automotive industry. Then, the reference case of the A-pillar structure is presented. The stakeholders of the A-pillar and their needs are identified through a systems engineering approach. These needs are translated into unambiguous requirements that further drive the conceptual design of the A-pillar. These requirements cover sustainability aspects and provide a basis for the sustainable design of the A-pillar. In addition, the functions of the A-pillar are identified and correlated with requirements to establish their relations.

2 SUSTAINABLE DESIGN APPROACH

2.1 Definition of sustainability

Sustainability is one of the greatest challenges of our time, addressing the urgent issues of climate change and resource scarcity. For this reason, it is crucial to integrate sustainability during the initial stages of the mechanical systems' design because this phase holds the greatest potential for impacting the systems' lifecycle [2,3]. Most efforts focus primarily on the environmental aspect of sustainability, emphasizing the reduction of a mechanical system's environmental footprint [2,3]. To a lesser extent, current efforts also address potential noise pollution, resource conservation, and waste management [2,3]. However, this approach falls short of observing the whole sustainability picture.

Sustainability has a holistic character encompassing a broad spectrum of potentially conflicting aspects emerging as a trade-off between them [2]. Based on this holistic consideration of sustainability, ''Engineering of Sustainability '' concept has been proposed by the Mechanical Engineering and Aeronautics Department (MEAD) at the University of Patras (UPATRAS), and it has been further developed in recent years, as demonstrated by several publications in peer-reviewed journals [2,3]. According to this concept, sustainability is considered a combination of performance, economic, social, environmental, and circularity aspects, referred to as pillars of sustainability [2]. **Figure 2** shows a general overview of this concept.

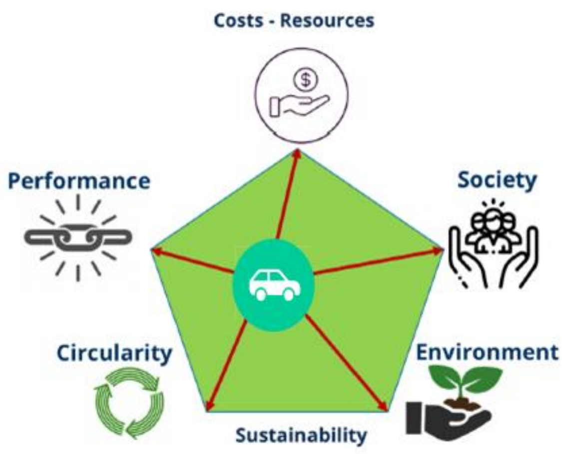

Figure 2: The ''Engineering of Sustainability'' concept [2,3].

Figure 2 illustrates that all pillars of sustainability are considered in the design of a sustainable component. These pillars are assessed together, providing a strong foundation for evaluating the overall sustainability of the mechanical system, such as structural components. A concise description of the sustainability pillars follows:

- **Performance pillar:** refers to meeting performance standards, including functional requirements, ensuring structural integrity, maintaining durability, and upholding safety and quality.
- **Economic pillar:** refers to the mechanical system's economic viability throughout its lifecycle requires evaluating costs associated with extraction, materials, manufacturing, maintenance, and end-of-life management, which demonstrates long-term economic advantages.

- **Social pillar:** addresses the broader societal implications of mechanical system design, primarily through material selection, including labor practices, community benefits, and worker safety, to ensure responsible production and usage throughout the material's lifecycle.
- **Environmental pillar:** refers to the minimization of the ecological footprint of the mechanical system across its entire lifecycle, from production to disposal, focusing mainly on CO_2 emissions.
- **Circularity pillar:** refers to the consideration of circular practices, such as recycling or remanufacturing, in the design of mechanical systems that comply with international regulations and standards (e.g. ISO 59020) aimed at resource efficiency and waste minimization.

Based on this concept, an aggregated metric of sustainability, namely the *Sustainability Index* (SI) has been derived by the authors, incorporating environmental, economic, social, and circular economy metrics and offering a structured, holistic, and compact methodology for sustainability assessment [2,3]. SI can be utilized to evaluate each variant of the conceptual design for a mechanical system, considering various geometries and materials.

In the A-pillar structure conceptual design, considerations of performance, economic costs, and environmental sustainability are considered due to a lack of literature studies focusing on the social and circularity impacts of A-pillar design and manufacturing. The outcomes of the sustainable conceptual design of the A-pillar structure and the evaluation with the proposed SI can provide a basis for future benchmarking against industry standards and research efforts within the Fun4Design project.

2.2 Sustainability in the automotive sector

Sustainability efforts in the automotive sector aim to minimize environmental impact, preserve resources, and ensure economic viability throughout a vehicle's lifecycle, from manufacturing to end-of-life disposal [4]. Different approaches have examined aspects of sustainability in the automotive sector namely circularity and minimization of material usage that have an immediate environmental and social impact [5].

In terms of circularity, remanufacturing has shown great potential. It was shown that old frame parts can be transformed into new, functional components that maintain comparable properties while reducing up to 40% the CO_2 emissions, as determined by energy consumption [6]. This trend was further supported by later Material Flow Analysis (MFA) and Life Cycle Assessment (LCA), which assessed the environmental and resource efficiency benefits of automotive remanufacturing in promoting material circularity [7].

The minimization of material usage focuses on the use of lightweight materials in vehicle structures. To this scope, a comparison between lightweight designs of steel and hybrid steel-aluminum against lightweight alternatives using ultra-high-strength aluminum alloys was made (6000/7000 series) [8]. The use of aluminum alloys leads to 39% and 45% weight reduction against steel and hybrid steel-aluminum alloys, showcasing significant environmental benefits including a 24–39% reduction in life-cycle global warming potential, determined primarily by the reduced fuel consumption.

The holistic consideration of sustainability in the conceptual design of automotive mechanical systems has not been presented in the literature. Studies that consider sustainability aspects in the design of automotive mechanical systems are limited only to assessing material configurations or material selection [8,9]. These works often lack a comprehensive examination of how the structure, material properties, and functional performance of automotive components interact to influence sustainability outcomes.

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3 REQUIREMENTS AND FUNCTIONS ANALYSIS OF THE A-PILLAR

3.1 A-Pillar as a reference case

The design methodology that incorporates sustainability needs is demonstrated in the conceptual design of the A-pillar. A-pillar is a critical structural element that supports the frame of a car and ensures the integrity of the passenger compartment. It is designed to endure extreme loads from frontal collisions and rollover accidents, manufactured from thin-walled high-strength steel alloys [10]. Literature studies have focused on improving the design of A-pillars to achieve lighter and safer automotive structures. Many of them have focused on introducing new materials to fulfil these goals while others explored geometric optimization [11, 12]. The configuration of the A-pillar previously examined in literature is considered as the reference case in the present study [13,14]. This reference case of A-Pillar design is illustrated in **Figure 3**.

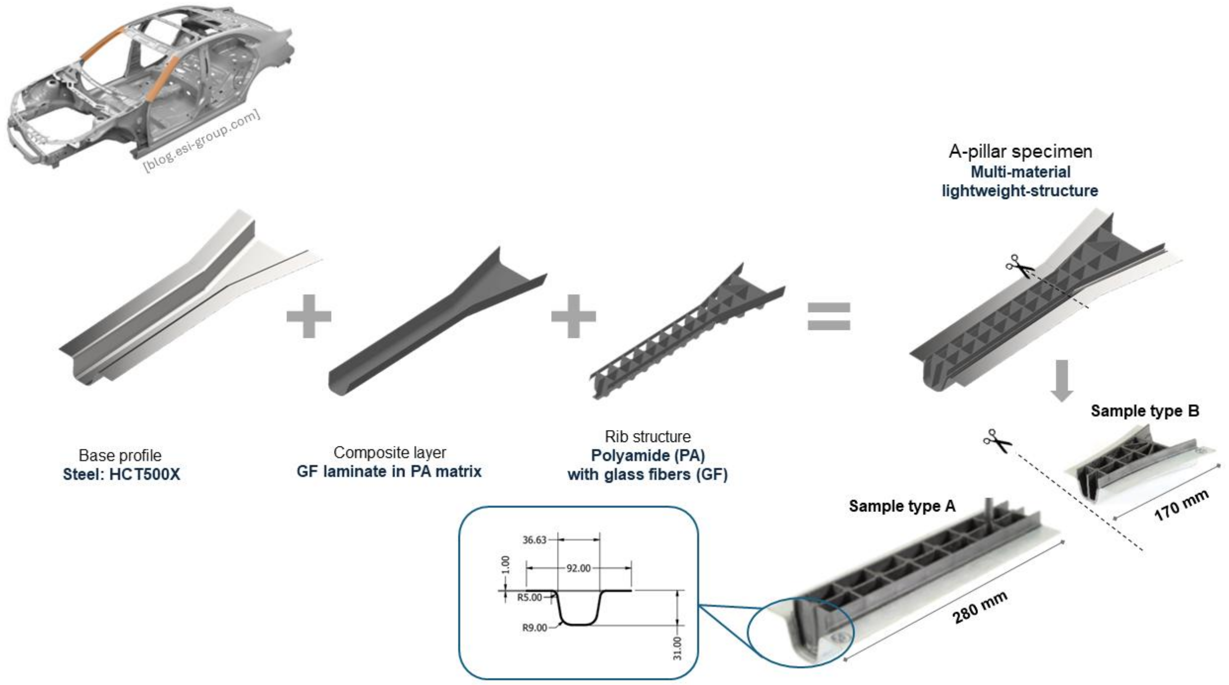

Figure 3: A-Pillar multi-material structure. The samples of type A and type B is indicated with base dimensions [13, 14].

The outer dimensions of the reference A-Pillar structure are 280×90×42 mm (length × width × height). A multi-material design approach was employed for this A-Pillar structure that resulted in a hybrid metal-composite structure consisting of three components:

(i) A metallic base profile made of 1.5 mm thick sheet Dual-Phase 500 (DP500) steel,
(ii) A composite of 2 mm thick layer made of glass fiber laminate (47 % fiber volume fraction) in polyamide 66 matrix, and
(iii) A composite rib structure with a rectangular configuration (4×2mm) and thickness of 2 mm made of polyamide 66 with 30 % (by mass) long glass fiber reinforcement.

The metal sheet is joined with the composite layer with adhesion bonding. The bonding between the rib structure and the composite layer is achieved through injection molding. More information about the fabrication of the hybrid A-Pillar can be found in relative literature [13, 14].

3.2 Definition of design requirements

To initiate the conceptual design of the A-pillar structure, its *stakeholders* and their *needs* shall be identified, translated to corresponding *requirements*, and then used as input to *conceptual design*. This is a necessary procedure to clarify the needs and to determine the requirements without ambiguity. An example of this approach is demonstrated in the relevant literature and is based on a systems engineering approach [1]. In the present case, the car is considered as the system and the A-pillar is a sub-system that fulfills the general needs of the system. It should be noted that the following stakeholder identification is not exhaustive but focuses on the key stakeholders and their needs that drive the sustainable design of the A-pillar structure [15].

Automotive manufacturers, passengers and regulation authorities are considered the key stakeholders. Their needs concern mainly the safety and the efficiency of the vehicle, as well as compliance with increasing environmental concerns. The latter concerns are increasingly gaining global recognition and are well documented in policies and regulations. Organizations such as the European Union (EU) have integrated them into regulatory frameworks and industry standards. As stated in the European Green Deal, sustainability guidelines aim to tackle resource scarcity and climate change challenges to ensure climate neutrality in Europe by 2050 [16].

Concisely **the needs** of the A-pillar structure as a vehicle's subsystem can be stated as:

- A-pillar needs to support the frame of the vehicle, ensure the passenger compartment, and withstand extreme loads from collisions and rollover accidents.
- A-pillar needs to be slim (have a small cross-section) to provide good visibility (small obscuration angle) to the vehicle's driver.
- The mass of the A-pillar shall be minimized to contribute to the overall vehicle's goal of reducing fuel consumption and improving efficiency.
- The manufacturing of the A-pillar should be cost-efficient, ensuring optimized material usage and minimal waste.
- The environmental impact of the A-pillar needs to comply with the sustainability guidelines of international regulatory bodies and industry standards for a minimized environmental footprint.

These needs are translated into clarified design requirements that will be used as input to the conceptual design of the A-pillar. These requirements can be categorized as structural integrity, safety, lightweight, environmental impact and cost requirements, to reflect the sustainability design pillars. Structural integrity, visibility and lightweight requirements can fall into the performance pillar, while environmental impact and cost requirements fall into the environmental and economic pillars of sustainability design, respectively.

Here is a detailed **list of requirements** stated with grammatical rules proposed by INCOSE requirements guidelines and applied in relevant literature [1,17]:

- **Structural integrity:**

The A-pillar shall be designed with a safety factor between 1.5 and 2.5.

The safety factor concerns only the static loading of the A-pillar structure in three-point bending that corresponds to the adequate need for the structure's structural support [15].

- **Visibility:**

The outer dimensions of the A-pillar, including the cross-sectional dimensions, shall be within those of the reference case.

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This requirement corresponds to the need for a slim A-pillar design to provide good visibility to the vehicle's driver [18]. The reference case design satisfies this need [14]. Thus, this requirement can be considered as a design constraint during the conceptual design methodology.

- **Lightweight:**

The A-pillar mass shall be 10% lower than the mass of the reference case.

The term lightweight refers only to mass reduction and not to the lightweight design requirements that consider the simultaneous fulfillment of structural integrity and mass reduction requirements. This requirement corresponds to the need for an A-pillar contribution to the overall vehicle mass reduction leading to the reduction of total fuel consumption [15].

- **Environmental impact:**

The CO_2 emissions of the A-pillar shall be 10% lower than those of the reference case.

This requirement corresponds to the need for compliance with sustainability guidelines for lower environmental footprint as expressed in the European Green Deal [16].

- **Costs:**

The costs of the A-pillar shall be 10% lower than those of the reference case.

This requirement addresses the need for a more cost-efficient mechanical system. The current investigation focuses on material costs, assuming comparable manufacturing methods [15].

3.3 Constraints, variables, and target parameters

The basic constraints, input variables, and target parameters (outputs) that will be considered during the conceptual sustainable design phase of the A-pillar are presented in **Table 1**.

Table 1. Constraints, variables and target parameters

Constraints	Input Variables	Target Parameters (Outputs)
• **Design space:** The main outer geometrical dimensions of the pillar should not exceed 280×90×42 mm. • The Safety Factor (**SF**) should be between 1.5 to 2.5. • No damage to the component should occur. • Use materials relevant for automotive structures.	• Cross-sectional profiles. • Thickness of base profile. • Thickness of composite layer. • Thickness of rib structure. • Materials of the components of the A-pillar.	• Stress components • Total mass • Environmental impact • Cost

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3.4 Identification of the A-pillar functions

Functions express the purposes a structure is manufactured for. In the case of A-pillar structure, the studied functions are the structural, safety, efficiency, economic and environmental functions. The description of the A-pillar functions and their relations with the design requirements is further elaborated.

- The **support structural integrity function** (**SI-SPT**) of the A-pillar is the ability to provide structural support to the frame of the car and to withstand sudden loading events, such as a frontal impact or a car rollout. In the present analysis, this is the main function and the requirement related to this function is the safety factor which should be between 1.5 and 2.5.
- The **impact structural integrity function** (**SI-IM**) of the A-pillar is the ability to withstand severe loading conditions to provide safety for the passenger.
- The **efficiency function** (**EFF**) of the A-pillar relates to its contribution to minimizing the car's fuel consumption. The requirement of the A-pillar mass being 10% lower than the reference case is related to the efficiency function leading to lightweight design aspects.
- The **environmental function** (**ENV**) of the A-pillar involves reducing the vehicle's environmental footprint through a mechanically optimized design that meets environmental regulations. This function is directly linked to the interconnected requirements of a 10% reduction in mass and CO_2 emissions compared to the reference case.
- The **economic function** (**COST**) of the A-pillar relates to its contribution to minimizing the total manufacturing cost of the vehicle. It is directly linked to the interconnected requirements of a 10% reduction in costs and mass compared to the reference case.

Each of these functions is linked to the A-pillar components, and during the conceptual design phase, the goal is to either increase or decrease them as needed. The relation between the functions and the A-pillar structural components is presented in **Figure 4**. During the conceptual design phase, the **COST** function is aimed to be decreased, while the other functions are intended to be increased. Most of the components serve the designated functions of the A-pillar, while the joints between the metallic base profile and the composite layer fulfil the SI-SPT function by bonding the metal to composite components, as well as to the COST function by affecting the total cost of the A-pillar structure.

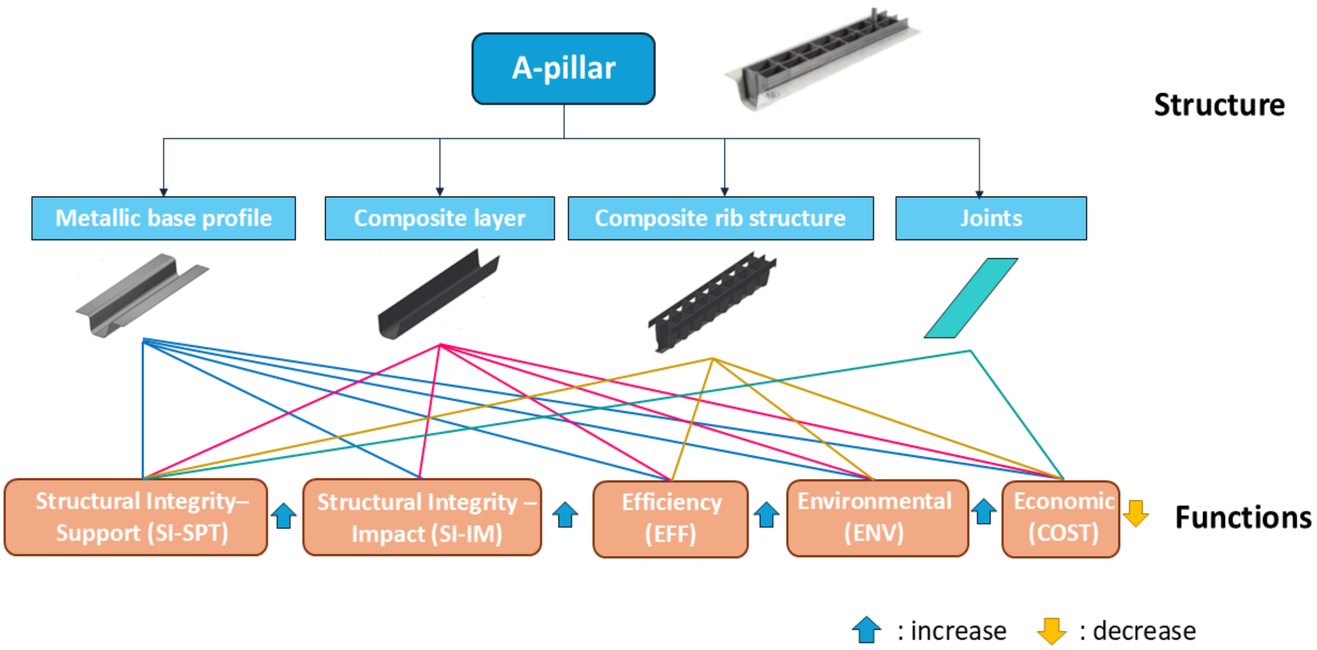

Figure 4: Functions and their relations with the A-pillar's components.

As observed, the main functions of the A-pillar align with sustainable design pillars. Thus, a **Design for Sustainability** approach can be followed, ensuring all functions are considered to identify the most suitable trade-off for a sustainable A-pillar design and to select appropriate metrics for design assessment. This evaluation will be conducted in the next design stage, where Structure-Property-Function (SPF) relationships will be analyzed in WP#3.

4 CONCLUSIONS

This deliverable presents the list of requirements and functions considered in the sustainable design of an A-pillar automotive part. First, the sustainability is determined as a trade-off between different aspects or pillars, namely: performance, economic, social, environmental, and circularity pillars. The consideration of all these pillars brings a holistic character to sustainability and only aspects of them have been considered in the current sustainable practices of the automotive sector.

Based on systems engineering approach, the stakeholder needs are identified and translated to design requirements. These requirements cover performance, economic, and environmental pillars of sustainable design. Then, the functions of the A-pillar structure are defined and correlated with design requirements. This correlation shows that the requirements cover the functions and facilitate the sustainable design of the A-pillar structure.

5 PROPOSED FUTURE ACTIONS

In the next stage of the Fun4Design project, the conceptual design of the A-pillar will be presented. This conceptual design approach will integrate the holistic character of sustainability as defined by the requirements presented in this report. A list of materials and geometric configurations will be examined and assessed during the conceptual design of the A-pillar. The assessment of the design variants will be performed with a finite element model analysis of the A-pillar structure combined with a sustainability assessment with the Sustainability Index. This procedure will identify the Structure-Property-Functions relationships and propose sustainable design options. The relevant results will be integrated into a deliverable with an appropriate level of information sensitivity.

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