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Optimizing civilian armored vehicle design with quality: A case study on lightweight ballistic protection using the DfA2 methodology

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Abstract
The global demand for ballistic protection systems within civilian armored vehicles (CAVs), particularly in high-security environments, necessitates focused research. Given the paucity of literature addressing the ballistic enhancements design of non-military passenger vehicles, this work concerns the analysis of quality assurance during the armoring process of a standard civilian passenger vehicle while maintaining its original functionality and consumer guarantees. To achieve these metrics, the article presents the Design for Assembly and Armoring (DfA2) methodology in a case study, examining the protection of a front door system of a worldwide compact sport utility vehicle (SUV). This systematic framework optimizes lightweight ballistic systems for CAVs through empirical evaluations and engineering principles. Integrating manufacturing acumen with Design for Excellence (DfX) principles, quality assurance protocols, automotive performance criteria, and ballistic defense requirements, DfA2 addresses the development and integration of armoring solutions with product and process quality in CAVs. Through field research, this study demonstrates the efficacy of the proposed method in refining armoring operations, minimizing armor material mass, and reducing production and design expenditures. Consequently, the findings of this case study with the adoption of DfA2 suggest that the method can be replicated or adapted for diverse vehicle categories, encompassing hatchbacks, notchbacks, SUVs, and commercial vehicles. This research sought to standardize vehicle armoring production, ensuring rigorous quality control while preserving original vehicle functionalities and consumer warranties.

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1. Introduction

Lightweight armored vehicles are typically designed for personnel protection, government agencies, the company's board of directors' fleet, or law enforcement, where mobility, security, and agility are crucial. The global civilian armored vehicles (CAVs) protection market continually grows, especially within regions characterized by elevated security requirements. Due to their specialized nature, production numbers vary widely yearly based on demand and geopolitical factors.

Generally, in companies that carry out armoring operations in civil vehicles, afterward produced at Original Equipment Manufacturers (OEMs), the automotive criteria and the dynamic performance characteristics of a standard vehicle project, such as fuel consumption, driveability, stability, noise, vibration, and harshness (NVH), ground vehicle weight (GVW) and disassembly procedures, are not fully met. In addition, automakers generally do not include ballistic protection issues in vehicle designs, which means that armoring companies, who do not usually have access to technical information from OEMs as well and there are no standard procedures for CAV production, have to carry out nonvalid interventions on the original vehicle body structures when performing part' disassemblies to allow the addition of armor components into the passenger cabin. These procedures can include making nonvalid cut-outs inside structured door panels or tailgates to enable access to the installation of bulletproof materials, which compromises the original torsional stiffness of the body-in-white or door-in-white, promotes premature corrosion, or even produces undesirable noises and vibrations.

OEMs rarely design passenger vehicles for ballistic protection, demanding post-production armoring modifications by specialized SMEs and medium-sized enterprises. These armoring companies must maintain compliance with OEM engineering specifications while delivering ballistically protected vehicles that meet stakeholder requirements and quality standards. However, operating outside OEM supply chains, these SMEs frequently omit implementing automotive quality standards, process controls, or design criteria (Boothroyd et al., 2010) and neglect to apply Design for Manufacturing and Assembly (DfMA) methodologies (Stylidis et al., 2020). Because of the limited scholarly literature on armoring passenger vehicles under manufacturing protocols and quality control procedures, particularly regarding lightweight ballistic protection integration, DfA2, Design for Assembly, and Armoring introduced by Candido and Kaminski (2023), which provides a systematic framework guiding SMEs by designing, assembling, and implementing ballistic protection while meeting automotive performance criteria and ballistic resistance requirements. In addition, based on the doctoral thesis related to light armor passenger vehicles from Candido, 2024, the authors presented a case study of the armoring design of the front-left door from an existing worldwide production compact SUV, a sport utility vehicle, to validate the employment of the DfA2 method, demonstrating the integrated consideration of design, manufacturing, assembly, and armoring development. Employing the DfA2 methodology, the researchers implemented ballistic protection for door system design and exploited relevant literature to reduce the armoring component mass while ensuring compliance with ballistic standards. This approach maintains the system's original functionalities and preserves consumer guarantees. Subsequently, the comparative advantages of the DfA2 method in weight optimization and cost reduction are analyzed.

1.1. Empirical considerations related to CAVs

Based on the empirical experience in automotive product quality and process audits since 2015, armoring companies usually adopt their in-house procedures, tools, and techniques to perform distinct designs and production processes for identical vehicles' protective parts from the same material protection suppliers. Indeed, as armoring companies typically have limited access to automotive criteria, the absence of specific procedures for armoring and integration with the automotive system results in a lack of agreement to OEM and ballistic protection requirements against handgun threats.

Given the independent operational status of most armoring SMEs relative to OEM supply chains, this research begins with employed qualitative empirical field studies to identify critical operational challenges in passenger vehicle armoring. Thereafter, evidence-based process improvement guidelines were formulated, aligning with established automotive engineering and ballistic protection principles. The correlation between identified challenges and best practices was derived from empirical analysis of existing armoring operational workflows within these SMEs, as introduced in Table 1.

Table 1. Challenges and correlated best approaches of CAV operations in researched armor companies (SMEs)

Challenges to armor CAVs		Best approaches to perform CAV operations at SMEs
1. Disassemble and reassemble the automotive parts	1a. Wide variety of car models and versions;	- Provide 2D/3D data and service manuals of the cars; - Follow OEMs' processes; - Establish standard works in armoring operations.
	1b. Reinstall the OEM parts over the armor components with no interferences.	- Perform 3D interface analysis between the ballistic and vehicle parts; - Comply with automotive criteria in the design.
2. Assembly stainless-steel components	2a. Perform parts' adjustments.	- Integrate 3D analysis with ballistic material suppliers; - Avoid welds, structural part changes or removals.
3. Assembly ballistic protection windows	3a. Manual assembly of large, heavy parts can harm the components.	- Handle the glasses with care and assure quality controls to safeguard component's integrity; - Produce fixtures to assembly armored glasses.
4. Installation of aramid or composite plates.	4a. Install flat plates on curved surfaces inside the vehicle.	- Comply with supplier guides of aramid or composite part installation on complex surfaces; - Identify curved surfaces inside the cabin that require ballistic protection.
5. Modifying existing automotive parts	5a. Adapt car parts to install armored pieces.	- Avoid welding or delete structural parts due to corrosion and stiffness concerns;
6. OEM and armoring certification requirements	6a. Restriction in automakers' references.	- Include BoM (Bill of Material) lists of car parts; - Scan the passenger compartment.
	6b. Challenges with ballistic material specifications.	- Include BoAM (Bill of Armored Material) list for armor parts; - Aquire parts' models for armor parts' design and assembly evaluations.

Through comprehensive empirical investigation conducted at multiple armoring facilities throughout Brazil, which maintains status as the global leader in CAV production volume, spanning the entire spectrum from protection system development to manufacturing implementation, Table 1 synthesizes the predominant operational challenges encountered during ballistic protection integration processes and their corresponding optimization procedures derived from systematic lessons learned references, strategic collaborative partnerships with OEMs for certified CAV production and quality assurance frameworks, and standardized assembly methodologies established by ballistic material suppliers.

The empirical investigation revealed that the most challenging ballistic protection integration procedures involve original component disassembly and subsequent reassembly operations, primarily attributable to armoring enterprises' lack of access to automaker references, two- and three-dimensional parametric models of standard vehicle configurations, and proprietary automotive procedures typically restricted to authorized dealerships and strategic stakeholders within the OEM supply chain. Therefore, the authors emphasize that SMEs perform these operations with limited automotive industry experience and ballistic protection knowledge. After producing the CAVs, the armor firms restrict to test them in city traffic and car wash evaluations without analysing more customer complaint details, such as noise on off-roads or bumpy roads, handling tests, and ballistic tests on the systems of the entire vehicle model. In addition, as armoring operations are considered handmade processes, Rosenqvist et al. (2024) asserted that such operations are often performed in the wrong order, parts are frequently misaligned, and several adjustments and checks of the assembly process are incomplete or omitted.

2. Literature review

Hence, the authors addressed the literature references based on the practical analysis of the civilian armoring vehicle segment. Understanding the concepts of DfX in assembly, disassembly, services, automotive, and ballistic references related to the armoring operation work proposal is crucial to meeting quality, reliability (Juniani et al., 2021), and customer expectation goals in this segment.

2.1. DfX, Design for Excellence

Design for Excellence (DfX) methodologies constitute a comprehensive framework oriented toward quality optimization and enhancement of customer satisfaction (Maltzman et al., 2005). The variable parameter "X" encompasses dual categorical dimensions: (a) operational factors, including cost efficiency, quality metrics, lead time reduction, process optimization, safety protocols, risk mitigation, and environmental impact assessment; or (b) specific product lifecycle phases such as manufacturing processes, assembly operations, distribution logistics, service implementation, or end-of-life disassembly procedures (Benabdellah et al., 2020). DfX enhances critical aspects, including technical performance parameters within targeted lifecycle phases and specific product attributes during the design development continuum (Mesa, 2023; Sassaneli et al., 2020). The objectives of DfX incorporate quality maximization, cost minimization, cycle time compression, operational flexibility augmentation, and significant productivity and efficiency improvements across the product development spectrum (Huang, 1996; Kuo et al., 2001). Therefore, Table 2 exposes the DfX references of DfD, DfMA, and DfS that fit armor operations.

Table 2. DfX methods and their applications to ballistic protection integration processes (adapted from Candido et al., 2022)

DfX method	Literature references	DfX approaches that fit passenger vehicle armoring operations
DfD	Mayyas et al. (2012)	Evaluate the disassembly efficiency of the reduced quantity of components.
DfD	Favi et al. (2019)	Optimize via Lean DfD product disassembly and end-of-life performance.
DfMA	Boothroyd, G. (1994)	Formulate streamlined assembly, minimize component inventory and integrate manufacturing design in the preliminary phase.
DfMA	Suresh et al. (2015)	Synthesize Design for Environment with DfMA to help assembly and reduce product mass and operation costs.
DfMA	Naiju (2021)	Implement DfMA in automotive components to augment quality, reduce component quantity and costs.
DfS	Dewhurst, Abbatiello, (1996)	Rationalize structure, encompassing fewer elements, reduced interfaces, and minimized fastening components or operations.
DfS	Dagman, Söderberg (2012)	Analyzed maintenance, repair, and service within Swedish automotive manufacturing entities.
DfS	Pastor, Mesa (2023)	Determine a repairability index for diverse products and delineate the procedural steps for complete product disassembly.

DfX demonstrates decisive relevance to ballistic protection integration operations through their comprehensive capabilities: facilitating systematic component disassembly, enabling reassemble component feasibility (DfD), optimizing manufacturing and assembly process sequences, mitigating unscheduled maintenance interventions and field recalls (DfMA), reducing maintenance requirements and associated cost and time factors, and implementing component and system standardization frameworks (DfS).

2.2. ADC, Automotive design criteria

The automakers maintain comprehensive responsibility for vehicle development—design criteria formulation, system integration, and validation protocols—and manufacturing operations, including stamping, body fabrication, surface treatment, and assembly (Kaluza et al., 2016). Automotive Design Criteria (ADC) constitute a multidimensional framework governing development across safety, aesthetics, functionality, and performance metrics, including aerodynamics, ergonomics, crashworthiness, fuel efficiency, mass optimization (Sarvankar and Yewale, 2019), and environmental impact. Additionally, ADC establishes specifications and evaluation methodologies for manufacturing processes to ensure production vehicles meet quality, durability, and performance standards while fulfilling consumer expectations and maintaining market competitiveness. The relevant ADC, related to civilian armored vehicles, are summarized (Candido, 2024):

- **Production**. To ensure manufacturability, engineers address product and process parameters that meet specifications during production. They implement statistical process controls, such as pre-control in subassembly processes (Sanches Jr. et al., 2008), maintain geometric tolerancing, incorporate error-proofing mechanisms, verify assembly feasibility, and preserve critical product properties. Validation methods utilize both physical prototypes and computational models to assess manufacturing constraints and capabilities (Hesse and Weber, 2012);
- **Safety**. Armored automobiles must maintain OEM design standards and government safety regulations. Although the added armor parts tend to increase the structural rigidity of the vehicle, which can enhance its ability to withstand road impacts and protect occupants, the excessive rigidity, especially using stainless steel and armored glasses, might lead to more force being transferred to occupants during a crash, increasing the risk of injury;
- **Electromagnetic interferences**. Adding ballistic armor to a civilian automobile, specially to plug-in hybrid or fully electric vehicles (EVs), introduces significant challenges related to electromagnetic interference (EMI). Metal armoring, such as stainless steel or aluminum, can act as a conductor or create unintended Faraday cage effects, altering the electromagnetic environment. Poorly grounded armor may result in stray electrical currents or arcing, which can disrupt sensitive systems;
- **Functionality**. Vehicle functionality is characterized by engine performance, active and passive safety systems, vehicle dynamics, and NVH. In CAVs, increased mass elevates the center of gravity (CG), compromising stability and handling, particularly during abrupt maneuvers. Thus it is necessary to enhance braking effort, resulting in decreased performance and accelerated brake wear. Furthermore, robust thermal management systems encompassing cooling capacity are critical, especially in high ambient temperature environments. Moreover, Happian-Smith (2002) noted that advancing electronic functionality is crucial for manufacturers to meet environmental regulations and rising consumer expectations;
- **Mechanical and corrosion resistances**. Automotive components experience multidirectional mechanical loading, requiring optimized material selection to balance strength, weight, cost, and durability. Modern vehicles primarily utilize high-strength steel, aluminium alloys, and engineered composites to achieve this balance (Davies, 2012). Despite manufacturer's advancements in corrosion prevention through surface treatments, vehicles remain vulnerable to electrochemical degradation (Chami et al., 2021). Effective corrosion resistance is essential, particularly for ballistic protection systems, requiring comprehensive strategies, including zinc electrodeposition, hot-dip galvanization, and specialized coating systems (Louda, 2007);
- **Payload**. Vehicle payload capacity, defines the maximum combined weight of cargo, occupants, and optional equipment, influencing OEM specifications for suspension, chassis, and braking systems. U.S. Dep. of Energy (2010) stated that the gross weight of a vehicle (GVW) is the weight of the empty vehicle plus the maximum payload the car was designed to carry. The Gross Vehicle Weight Rating (GVWR), established by OEMs, represents the maximum safe operating weight determined by the load-bearing capacity of structural components (Happian-Smith, 2002). Figure 1 shows payload, GVW, and GVWR, vital to passengers' safety and security.

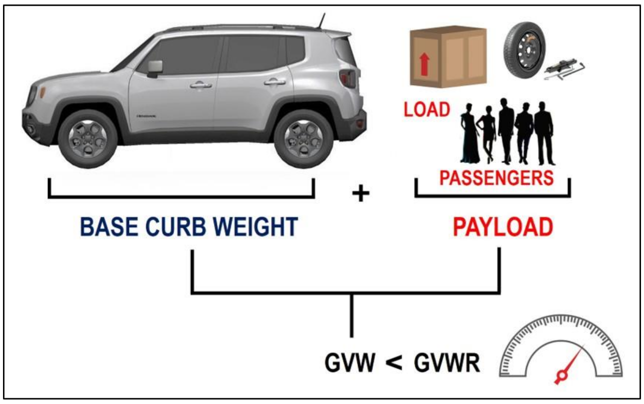

Fig. 1. Key weight parameters for passenger vehicles

The inherent complexity of automotive criteria demands that SMEs implement rigorous enhancements in quality assurance, process control, repeatability, and continuous improvement across their design and manufacturing operations. Consequently, ADCs provide a critical framework for establishing a robust system that substantially benefits the armor firms. Specifically, ADCs empower companies to execute operations that satisfy OEMs and customer specifications (IATF, 2016; Benabdellah et al., 2020).

2.3. Automotive quality

Product quality problems manifest as product nonconformities and defects; products with such problems are called nonconforming or defective products (Knop and Gejdos, 2024). In the automotive sector, Pacana and Czerwińska (2020) assert that product quality is a critical determinant of customer satisfaction, loyalty, and brand reputation. Furthermore, Hąbek et al. (2023) corroborate the significant role of product quality in the automotive industry, emphasizing that customer expectations encompass vehicle safety, durability, and functionality. Substandard product quality inevitably results in safety hazards, mandatory recalls, and escalated manufacturing costs. Consequently, rigorous production process monitoring and stringent quality control are indispensable for sustaining a competitive market position. These principles unequivocally apply to producing and integrating ballistic protection components in passenger vehicles, ensuring comprehensive vehicle quality and customer confidence.

Moreover, the automotive industry employs quality tools to ensure product reliability, enhance manufacturing processes, and achieve customer satisfaction, including the Seven Basic Quality Control Tools, Failure Mode and Effects Analysis (FMEA), Statistical Process Control (SPC), and the Eight Disciplines (8D) Problem-Solving Method. These tools facilitate the prevention of defects and nonconformities, process improvement, and systematic problem resolution in automotive manufacturing.

Multiple critical factors determine product quality in the automotive industry, including design, engineering, manufacturing processes, and supplier quality. The sector has decisively embraced advanced technologies such as artificial intelligence and machine learning to enhance product quality and minimize defects (Hua et al., 2023). Baraldi and Kaminski (2018) pointed out that companies remain vulnerable to product quality variability, with failures trespassing internal quality assurance barriers despite preventative measures. These nonconformities directly result in vehicle recalls, as severe quality defects compromise the integrity of customers.

Therefore, as Goicoechea and Fenollera (2012) emphasized, the quality assurance of materials and components sourced from suppliers has become a critical determinant in product success and organizational sustainability. This strategic imperative directly influences both operational effectiveness and long-term market viability.

2.4. Ballistic protection in automobiles

The design of ballistic protection systems presents an engineering challenge, requiring critical decision-making across economic, regulatory, logistical, and technical domains. In this study, the authors rigorously adhered to established international standards, namely the National Institute of Justice (NIJ), Publicly Available Specification (PAS) 300, and the American Society for Testing and Materials (ASTM). Specifically, NIJ Standard 0108.01, encompassing protection levels I to IV, demands requirements for ammunition type, projectile velocity, and the number of impacts that vehicle ballistic materials must withstand (DoD, 1985). Furthermore, British Standards Institution (BSI) PAS 300 (BSI, 2018) defines test protocols for CAVs, evaluating performance against ballistic impacts (including handgun, shotgun, and rifle), side blast, under-vehicle blast, and roof blast scenarios. This standard also incorporates Fragment-Simulating Projectile (FSP) tests as a component of ballistic assessment. Moreover, the ASTM E3113-23 standard (ASTM, 2023) establishes criteria for ballistic-resistant panels for vehicle doors under small arms guaranteeing a standardized security level.

To perform automotive ballistic testing, certification agencies develop a rigorous shooting map that is represented on the vehicle's surface (Figure 2). This shooting map strategically delineates each projectile impact's location and sequential order, primarily focusing on identifying and targeting ballistically vulnerable regions, such as door and panel interfaces or glass edges (Shim et al., 2016). Determining the shooting map's points and caliber-specific positional distribution is contingent upon an evaluation of the vehicle's design, model, identified vulnerable areas, designated ballistic protection level, corresponding calibers, and the established armoring design (Candido, 2024).

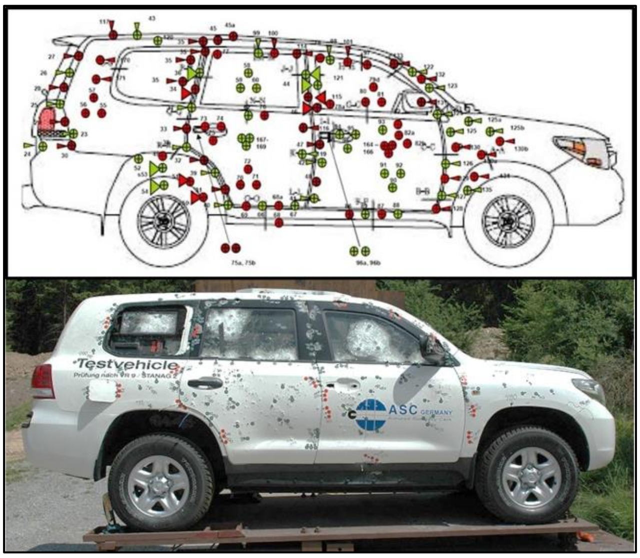

Fig. 2. Example of shooting map layout and ballistic test in a CAV

These standards and procedures presented allow the definition of evaluation criteria and test parameters at armoring firms, which must be carried out so that a test is normalized, internationally understandable, and, therefore, repeatable. International standards also include test range ambient conditions, details and marking of targets in the vehicle, especially the weak points, location of the different hits on the target, specific treatments that the targets have to undergo before testing, target positioning and inclination, test impact validity assessment, component performance definition, and how to report a ballistic test (Pellegrini, 2020).

3. DfA2 methodology

The Design for Assembly and Armoring (DfA2) methodology establishes a systematic and comprehensive framework for integrating ballistic components into a vehicle's passenger compartment while maintaining automotive functionalities and protecting occupants from ballistic threats (Candido and Kaminski, 2023). The methodology incorporates DfX disciplines at strategic stages: DfD, DfMA, and DfS. These tools standardize vehicular armor operations, optimize quality products and processes, and enhance customer satisfaction by delivering high-quality, lightweight ballistic protection that preserves vehicle performance, maneuverability, and comfort.

SMEs in the aftermarket armor industry must adhere to ADC when implementing armor systems in CAVs. These criteria, aligned with OEM standards, ensure the maintenance of automobile design and functionality while protecting original components. Safety systems demand particular attention—airbags, sensors and wiring harnesses must maintain their original positioning and interfaces. Critical considerations include payload limitations, corrosion resistance, crashworthiness, occupant protection systems, lightweight body materials, and vehicle safety systems (Happian-Smith, 2002; Du Bois et al., 2004). DfA2 encompasses technical imperatives: compliance with ballistic protection standards, strategic material selection, structural design integrity, ergonomic optimization, and vehicle dynamics enhancement. CAVs requires appropriate suspension, braking, and other adjustments while maintaining payload distribution and component interface integrity.

3.1. Case study

The case study applied the DfA2 in an armoring operation of a front left door system, FLDS of a compact SUV vehicle in current worldwide production, displayed in Figure 3 with the respective original gravity center (GC) point.

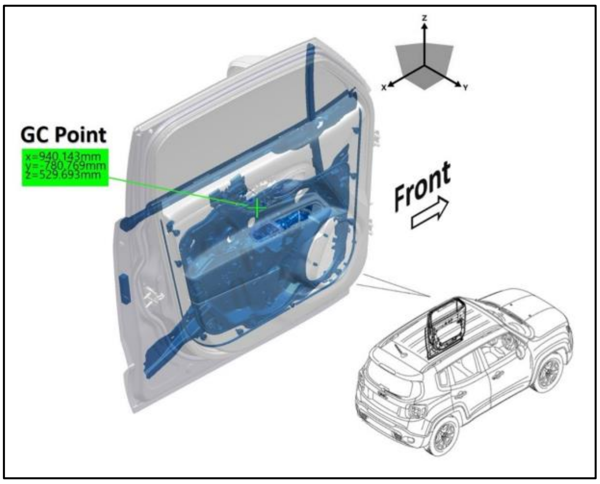

Fig. 3. FLDS of a worldwide compact SUV with GC point

Therefore, this study presented an armor design following the steps of the DfA2 method because it is critical and representative of the driver's security and the entire armoring vehicle operation. Indeed, the FLDS is a high-complexity system for armoring since it contains structural parts, sheet metal panels, moveable parts, glazing and door lock cables, impact beam bar, side impact sensors, window lifter module, wiring harnesses, weatherstrips, and finishing parts, such as door trim panels.

Moreover, OEMs consider the door structure's stiffness and strength as part of vehicle performance, which is relevant in automotive design and validation. There are also impact homologation requirements for the door's anti-intrusion aspect. Thus, the authors conducted a virtual simulation of a 3D model of FLDS components from a current production of a compact SUV using automotive software, CATIA v5, Computer-Aided Three-dimensional Interactive Application version 5, from *Dassault Systèmes* company. In addition, the authors used CATIA v5 to design the armor parts and to install them in the 3D FLDS considering the DfX tools, ADC, ballistic protection. Hence, Figure 4 illustrates the DfA2 applied for an armor operation of an FLDS in the manufacturing environment. The blue steps of the DfA2 flow model (blue dots 1, 2, 3, 4, 5, 6, 11, 14, 19, 23, 23A, and 25) consist of the SME's most common field operations.

In contrast, the yellow dot steps (7, 8, 9, 10, 12, 13, 15, 16, 17, 18, 20, 21, 22, and 24) are considered critical operations based on empirical research, including product development, assembly, tests and validations, production process audits and the start of production. The application of DfA2, within the context of automotive-specific DfX principles, is particularly relevant for the 'yellow dot' critical stages of vehicle armoring operations, due to the inherent disassembly, assembly, and serviceability requirements. Therefore, the authors conducted a virtual ballistic test employing an exhaustive analysis of the FLDS to validate the case study. This analysis simulated the intrusion of 9 mm and .44 Magnum projectiles in different attack angles on the external surface of the FLDS, consistent with NIJ 0108.01 IIIA ballistic level, using 3D models of this door assembly and ballistic protection components, on DfA2 stages 7-10.

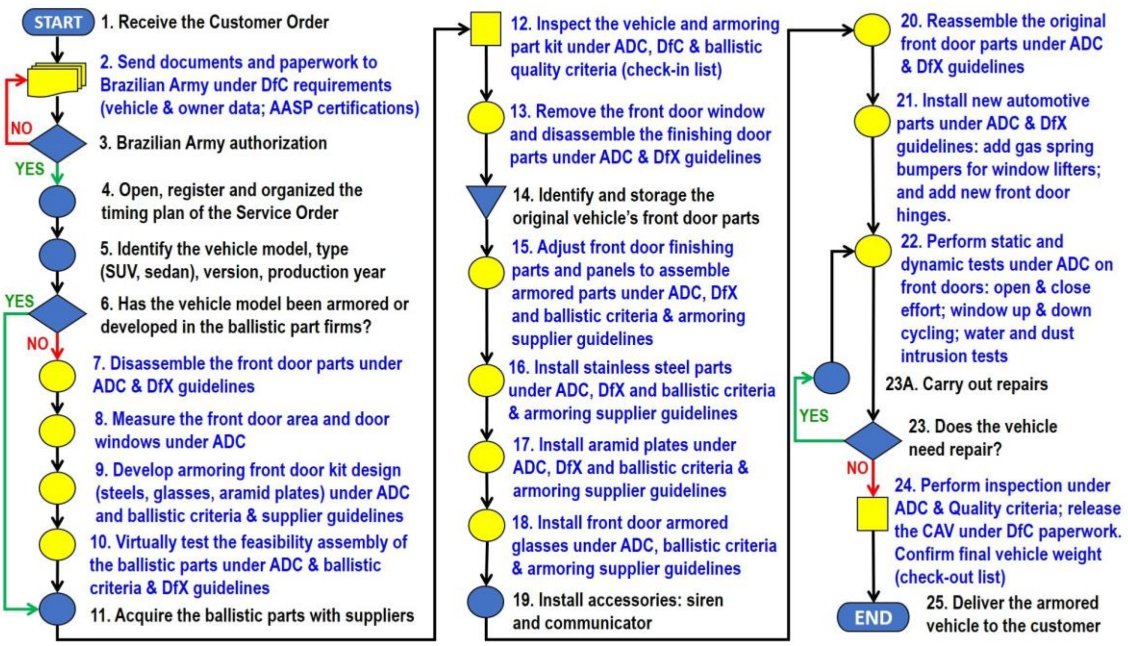

Fig. 4. DfA2 methodology applied to armor a FLDS

Figures 5 and 6 provide empirical corroboration of the armor design's efficacy, illustrating key FLDS cross-sections and the projectile trajectories with the armor parts strategically designed and positioned, thereby demonstrating the integration of automotive and ballistic requirements.

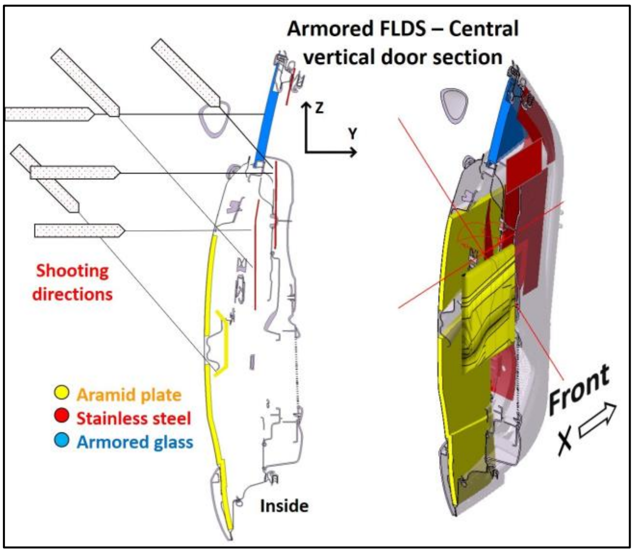

Fig. 5. Shooting directions in the YZ section of armored FLDS

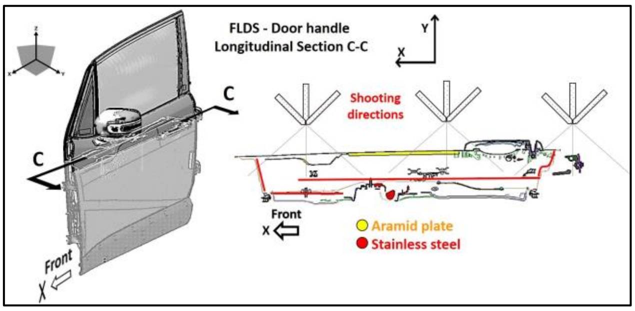

Fig. 6. Shooting directions in XY section of armored FLDS

Armor design of the FLDS followed standards NIJ 0108.01, ASTM E3113-23, and PAS 300:2018. The analysis encompassed a vulnerability assessment, checking design elements around door apertures, handles, latches, locks, armor joints and overlaps, cover plates, and glass structural supports and framing. Scanning vertical (ZY) and horizontal (XY) cross-sections throughout the armored FLDS confirmed the absence of vulnerabilities. The DfA2 method facilitated installation and positioning of ballistic components within CAV door, ensuring compliance with OEM standards and preventing interference or malfunction within integrated automotive systems. An evaluation of armored FLDS cross-sections validated the absence of interferences, functional impairments, gaps, or flush discrepancies between automotive and ballistic parts.

4. Results and discussion

According to a rigorous cross-sectional analysis, Figure 7 presents a comparative evaluation of the original and armored FLDS, specifying each GC and the incorporation of opaque and transparent armor parts. The armored FLDS achieves compliance with NIJ, ASTM, and PAS standards, thereby ensuring the mitigation of all identified vulnerabilities. Furthermore, the door lock mechanism and armored windows maintain unimpeded functionality, mirroring the original design.

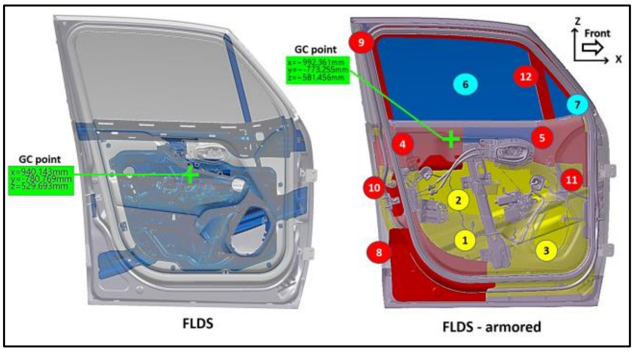

Fig. 7. Current and armored FLDS based on the DfA2 method

Consequently, all ballistic protection components designed for the FLDS were compiled into a Build of Armored Material (BoAM) list. This BoAM, analogous to an automotive Bill of Materials (BoM), provides technical specifications for each ballistic component, including part name, part number, quantity, material type, and dimensions. Table 3 presents these components, specifying name, dimensions, mass, and material, establishing a component control and traceability tool.

Table 3. Build of Armored Material (BoAM) added at front door

Item	Part name	Dimensions (mm)	Mass (kg)	Material
1	Side bar cover	863 x 226 x 5,0	1,42	AF
2 / 3	Upper and lower cover	955 x 757 x 5,0	3,37	AF
4	Inner lock cover	344 x 210 x 2,0	1,19	HSS
5	ORVM inner cover	207 x 205 x 2,0	0,61	HSS
6	Fixed armored door window	190 x 400 x 18	1,25	G+P
7	Armored door window	720 x 520 x 18	15,09	G+P
8	Lower rear cover	395 x 310 x 2,0	1,46	HSS
9	Upper frame cover	905 x 475 x 2,0	1,22	HSS
10	Outer lock cover	63 x 210 x 2,0	0,18	HSS
11	Inner panel cover	127 x 572 x 2,0	0,88	HSS
12	Fixed window channel cover	49 x 367 x 2,0	0,26	HSS

Legend: ORVW = Outside rear-view mirror; AF = Aramid Fibers; HSS = High Strength Steel; G+P= Glass plus Polymers.

Using CATIA v5 software, the authors defined each ballistic protection component's mass and dimensional properties following the DfA2 method. Integrating ballistic protection materials in strategic locations ensures reliable coverage of vulnerable areas, resulting in an 82% increase in the total mass of the armored FLDS, reaching 60 kilograms (kg) of total mass. This result represents an addition of 27 kg over the original FLDS assembly mass of 33 kg. On the other hand, the field research at armor firms indicates for the same vehicle door assembly an average mass addition of 40 kg of protection parts, which means a 48% of mass increase relate to the 27 kg achieved with the DfA2 method. Therefore, DfA2 contributed to cost and mass reduction in the armored FLDS design.

Additionally, Table 4 delineates the DfX, ADC, and ballistic references for critical armoring process steps of the FLDS case study, as implemented via DfA2, which demonstrates the relevance of these parameters in the critical 'yellow' stages of the armoring process. These recommendations are generalizable to any automotive platform or vehicle system requiring armoring, as the procedures are not specific. The authors aim to illustrate the armoring process for a complex system, encompassing fixed and movable components, where transparent and opaque are integrated within the FLDS.

Table 4. Application of DfA2 method for armor FLDS

Critical armor operation step	DfX tools	Automotive Design Criteria	Ballistic protection guides
7. Disassemble the original parts.	DfD	Comply with OEM parts procedures	Check ballistic weak areas after disassembly
		Avoid damage parts	Predict ballistic protection parts
8. Measure the parts and their interfaces.		Perform measurements based on 3D and 2D part models	Consider the minimum area for ballistic protection
9. Develop armoring kit: steel, glasses, aramid parts.	DfMA DfS	Consider self-extinguishing properties in the ballistic parts	Comply with NIJ-IIIA standard
		Design with no interferences	Perform ballistic overlaps based on supplier's specs.
10. Validate, test, and assemble the ballistic parts.	DfMA	Consider the OEM's tolerances and interfaces.	Provide Ballistic Certifications for each armor part
12. Inspect the vehicle.		Inspect the FLDS under OEM specs	Inspect the ballistic parts Follow armor supplier's specs
13. Remove original parts.	DfD	Comply with OEM parts procedures	Check possible ballistically vulnerable areas
		Avoid damaging the FLDS parts during disassembly	Predict which ballistic protection must be installed.
15. Adjust door parts.	DfMA	Follow OEM guidelines for gaps and flushes	Avoid interferences between parts
16. Install stainless steel parts.	DfMA DfS	Assembly of the stainless-steel parts without interferences	Follow stainless steel part supplier requirements.
17. Install aramid plates	DfMA DfS	Assembly without interferences	Follow the aramid plate supplier product and process specs.
18. Install armored glasses	DfMA DfS	Armored glasses assembly under OEM specs.	Follow armored glass supplier procedures.
20. Reassemble OEM parts	DfMA DfS	Reassembly of the automotive parts under OEM requirements	Check all ballistic parts installed; No damages allowed to any parts.
22. Perform static and dynamic tests.		Perform cycling, NVH, dust and water intrusion	Perform ballistics tests on similar samples
24. Inpect the CAV and check weight.		Inspect the CAV based on OEM specifications	Check all ballistic protection parts installed.

At step 8, engineers measure the FLDS and consider the original interface of OEM parts to preview ballistic protection component installation within the door. In step 9, ballistic protection development, engineers define the protection area and conduct a feasibility assembly analysis of protection components based on critical cross-sections performed on the 3D door model. Armor components must comply with minimum ballistic protection area requirements and OEM design specifications, considering the DfX tools and techniques used during the armoring operations. Moreover, facing iterative developments and product changes, Morris et al. (2015) assert that engineers should design and monitor product characteristics to ensure compliance with legislation, standards, and customer requirements. Therefore, under automaker references, the armored FLDS must maintain OEM tolerances between components, ensure serviceability for door lock and power window lifter maintenance (DfS), preserve critical safety systems, such as crash beam and sensors, and guarantee operation of the door glass and its support mechanism. Engineers must also consider precise clearances in water drain holes and prevent water leakages.

Regarding the ballistic protection references, opaque components must have no burred edges and cannot loosen during vehicle movement or a crash, following the automaker criteria. Moreover, the aramid plates must be installed in flat and large areas, complying with minimum overlaps between ballistic protection components. Furthermore, the design of stainless-steel parts has to ensure that all tightening in the passenger compartment structure after the armoring process has enough screw length and clamping force according to OEM torque specifications (Candido, 2024).

In this case study, the authors conducted critical cross-sectional analyses of the front door using 3D model of the FLDS (DfA2 step 10) to identify ballistic vulnerability areas during detailed armor design. Thus, we analyzed edge regions and limited space areas within the door to virtually install ballistic protection components, such as those around the door lock or in areas where automotive components require focus on disassembly (DfD) and serviceability (DfS).

5. Summary and conclusion

This work initiated with a review of the core tenets of the Design for Armoring and Assembly (DfA2) methodology. This systematic framework, integrating Design for Excellence (DfX) principles, Automotive Design Criteria (ADC), and ballistic standards, effectively assists the seamless installation of opaque and transparent ballistic protection materials into automotive systems. The DfA2 guarantees adherence to stringent lightweight ballistic standards and Original Equipment Manufacturer (OEM) specifications, while concurrently eliminating interference with original automotive components. The efficacy of DfA2 is substantiated by empirical research conducted across eight Small and Medium-sized Enterprises (SMEs) specializing in vehicle armoring. This research demonstrates the methodology's capacity to optimize ballistic protection and ensure vehicle performance in accordance with rigorous quality and operational references. Consequently, DfA2 establishes definitive guidelines for armoring operations, which are frequently characterized by a lack of standardized procedures and comprehensive OEM knowledge (De Fazio et al., 2021; Abuzied et al., 2019). These outcome in consistent manufacturing processes and enhances production quality controls.

Therefore, this paper demonstrated the applicability and efficacy of the DfA2 methodology through a case study focused on the armoring of a FLD) in a globally produced compact SUV. The research establishes the method's advantages in achieving OEM and ballistic protection requirements, significantly reducing production time and development costs, minimizing mass, enhancing design accuracy, and optimizing material utilization. Employing CATIA v5, a current automotive design software, for armored component modelling, the study conducted an evaluation of interface areas within the FLDS. This virtual analysis, extending the established principles of comprehensive optimization and testing as described by Hirz et al. (2013), yielded substantial reductions in development time and costs. Structural integrity analysis within the armoring design confirmed that the usage of advanced protective materials, including aramid fibers and ultra-high-molecular-weight polyethylene (UHMWPE) (Bao et al., 2022), did not compromise the FLDS’s structural performance.

Furthermore, the ballistic protection parts were designed to be electromagnetically inert, ensuring compatibility with the vehicle's electronic systems. The authors designed the armored FLDS under the DfA2 to keep the original functionalities and safety features. Thus, based on the results, the authors considered that the study's aim had been achieved.

In CAVs, the external appearance and aerodynamics remain unchanged. Normally, homologation process is not required after armoring when the additional protection materials do not exceed the vehicle's GVW limit. However, SMEs must obtain prior authorization from the government authorities or the Army due to the inclusion of ballistic protection materials classified as controlled materials. Furthermore, DfA2 incorporates automotive static and dynamic testing protocols, including door cycling and effort tests, electrical system checks, and driving performance evaluations, to comply with automotive standards and OEM requirements.

5.1. Strengths and limitations

The scientific contribution of this work lies in its enhancements of a comprehensive, organized framework for developing and qualifying armor passenger vehicles, a field primarily dominated by military vehicle-centric research and references related to ballistic material properties. The systematic organization of references within the DfA2 method, validated through the FLDS case study, provides a valuable framework for future armored vehicle developments. By adopting the DfA2 in armoring firms, the authors considered this method a roadmap reference for armoring the entire vehicle of any civilian automobile type or model and at any other ballistic level, from the design to the shop floor process and final vehicle delivery. The procedures and controlled operations of DfA2 can reduce stop orders, avoid risks of manufacturing errors, and enhance quality control in an assembly line. This method establishes a starting point for future scientific investigations and practical applications.

On the other hand, the case study presented was limited to armoring an FLDS of one type of vehicle in a static condition and at one level of ballistic resistance (NIJ IIIA). The limitations of using the DfA2 may be related to the difficulty of SMEs in following the systematic steps of armoring operations, requiring to purchase and training the specialists in Computer Aided Design and Engineering (CAD/CAE) software licenses to carry out the development of the armor projects, to obtain quality certifications, such as ISO-TS-16949. To minimize these difficulties, the authors recommend that SMEs establish partnerships with automakers and ballistic protection material suppliers with government agencies linked to research and development initiatives to obtain financial resources for these investments.

5.2. Future works

In future works, SMEs could analyse the CAVs in CAE software for dynamic evaluation and perform physical ballistic tests to confirm the DfA2 effectiveness and verify eventual deviations or even possible projectile ricochet situations. Moreover, in the design phase, the interface between the armor and vehicle safety parts must be verified by automakers and manufacturers of armored parts criteria.

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