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Review of Practices to Integrate Aircraft Mass Properties Management and Development Processes

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ABSTRACT: The mass properties of aircraft directly influence their performance and costs, and are particularly subject to high uncertainties in the early phases of the development process. As aircraft systems become more detailed, their mass properties are iteratively updated. Those updates, in turn, may lead to rework on aircraft systems. To avoid excessive iterations, aircraft manufacturers employ the mass properties management (MPM) process during their development processes. However, even when this approach is adopted, the continuous cycle of increasing weight and redesigning aircraft structures represents a significant challenge, which may lead to the cancellation of programs. One of the causes of this problem is inefficient integration between MPM and the aircraft development process. We propose a concept to significantly enhance the integration between MPM and aircraft development processes, suggesting feasible practices to support its implementation. The research methodology combines a review of the literature, an exploratory case study, a three-year longitudinal case study, and verification by experts. The results describe a concept for integrating aircraft MPM and development, supported by 16 practices. They also include a characterization of the MPM process based on literature and practices, which lists 17 characteristics divided into four categories: Goals/Strategy, Activities/Information, Resources/Tools, and Organization/Roles and Responsibilities.

KEYWORDS: Systems engineering; Product development; Mass properties.

INTRODUCTION

Weight and other mass properties (such as the center of gravity and moments and products of inertia) are essential for the performance of an aircraft, such as cruise efficiency, payload, range, etc. (Gnadt *et al.* 2019; Raymer 2012, de Weck 2012). For example, reducing an aircraft's weight by 30% leads to a 7% to 15% reduction in fuel consumption (Amoo 2013; Greene 1992). Likewise, the empty weight of aircraft is an important piece of information in cost estimation methods employed in the early phases of development (Curran *et al.* 2004; Nicolai and Carichner 2010; Raymer 2012; Roskam 1990), when information about actual masses is still unavailable (Heim and Pertermann 2008). Furthermore, mass center and moments of inertia strongly influence layout optimization (Lau *et al.* 2014).

Given the impact that modifying mass properties may have on aircraft performance and costs, these properties should be tracked and managed throughout the development process. Therefore, aircraft manufacturers normally employ Mass Properties Management (MPM) during their product development process, following recommended practices such as the SAWE RP-7 (Society of Allied Weight Engineers) (SAWE 2004) and technical overviews such as the SAWE TO-1 (SAWE 2018). The purpose of MPM is to ensure that the aircraft's mass properties are in line with its performance requirements (SAWE 2004). The process

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provides accurate and timely reporting of mass properties to the chief engineer, who is responsible for making decisions about cost balancing, scheduling, and performance requirements (SAWE 2004).

MPM must be integrated into the aircraft development process (Stegmiller *et al.* 2018), which, in turn, usually follows an iterative and concurrent approach employing both top-down and bottom-up strategies (SAE 2010). This integration is complex and requires the use of highly iterative information. For example, realistic estimates of empty weight and other mass properties are necessary as early as in the conceptual design (Gnadt *et al.* 2019). Modifications of mass properties in later stages of the design will lead to iterations back to conceptual definitions. Therefore, all the mass properties of an aircraft must be strictly controlled during its development.

Previous experience indicates that the weight of any vehicle tends to increase during design, manufacturing, and validation (Boze and Hester 2009), and this increase has severe consequences. For example, if the empty weight of an aircraft increases during the design process, it will require a proportional increase in takeoff gross weight to maintain its ability to perform the mission for which it was originally designed. Extra weight in the aircraft structure requires additional wing area for higher lift, additional engine thrust, and additional fuel to provide the same range. Hence, the addition of 1 lb in structural weight results in an increase of 2 to 10 lb in the aircraft's weight (Greene 1995). This problem of iterative weight increase also affects the surface control effectiveness and control systems gains. Therefore, such excessive iterations of the various subsystems of the aircraft contribute to program delays (Kraft 2010).

Many aircraft programs have been canceled due to excessive delays resulting from the continuous cycle of increasing weight and redesigning aircraft structures (Andrew 2001). In fact, this is a constant issue in any new aircraft development. One of the causes of the low effectiveness of MPM is that the area responsible for mass management usually works in an ad-hoc way, i.e., the MPM and product development processes are not properly integrated.

This paper aims to address these shortcomings by proposing a concept to coordinate and improve the integration between the MPM and aircraft development processes in order to achieve more predictable mass properties and reduce iterations in the development process. This concept is implemented through a set of proposed tangible practices, which are based on systematized MPM process dimensions (functions, roles, rules) in the context of an aircraft manufacturer. Our contribution to the theory is the proposal of a structured and coordinated integration of the two processes. Practitioners could apply this proposal to replicate the procedure in their own organizations, defining possible improvements to implement the proposed practices. Companies that develop vehicles other than aircraft can also use the practices as inspiration for MPM and product development integration in their own contexts. The methodology employed here consists of a literature review, an exploratory case study, a three-year longitudinal case study, and verification and validation by experts. The aspect that distinguishes this paper from other articles in the literature is its holistic and integrated approach of analyzing the MPM process and comparing it with the theory, as well as describing the results of a real case based on a world-class aircraft manufacturer. This paper is divided into six sections: Introduction; Mass Properties Management (MPM) – Theory; Methodology; Case studies, synthesis, and practices; Verification of the proposal; and Conclusion.

MASS PROPERTIES MANAGEMENT – THEORY

AIRCRAFT DEVELOPMENT PROCESS AND MPM

An aircraft development process is defined according to the context, company, type of aircraft, and other factors. In order to employ a common vocabulary for the development process, this paper divides the aircraft development process using the structure proposed by Torenbeek (2013), as shown in Fig. 1. In this figure, the first stage consists of the aircraft's conceptual design and addresses basic issues such as its configuration, size, weight, and performance, among other factors. In the second stage (preliminary design), engineers design and analyze the aircraft systems for which they are responsible (Raymer 2012). The third stage consists of the detailed design phase, when the final parts to be manufactured are designed. This is the phase in which the entire aircraft is broken down into individual parts (Raymer 2012). The subsequent phases (manufacturing and testing phases) end with the granting of a Certification of Airworthiness and the first delivery to the customer (support design) (Torenbeek 2013). At the bottom of Fig. 1, note the MPM process embedded throughout the entire development process:

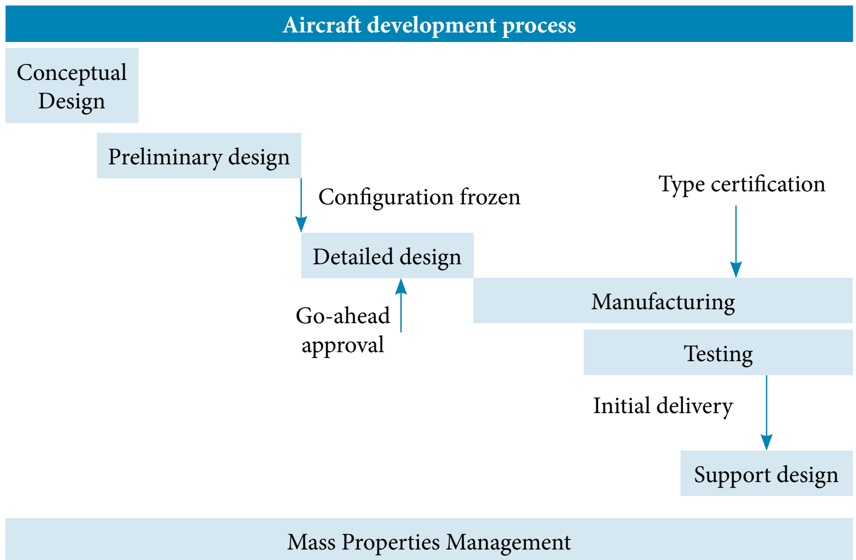


Figure 1. Aircraft Development Process (adapted from Torenbeek 2013).

MPM is present in every phase of the aircraft development process, and must be adapted to each maturity level of this process (Boze and Hester 2009). Andrew (2001) studied the development process of four different aircraft and found that all the designs had problems involving the control of weight and other mass properties, negatively affecting their performance and leading to delays in product delivery. Table 1 describes this variance in aircraft and program metrics of those four aircraft, which is expected. The analysis of variance in aircraft metrics considered the difference between the metric that was initially specified (in the conceptual design phase) and the metric upon entry into service. The analysis of program metrics considered the number of months of delay of some major milestones (first flight, type certifications, and initial delivery) when compared to the initial planning.

Table 1. Variance of aircraft and program metrics in four aircraft programs (adapted from Andrew (2001).

Aircraft metrics/ Program metrics	Bush BA140	SW-24	M700	SW-40
Empty Weight	+21%	+7%	+36%	+12%
Payload	+16%	+3%	-18%	+7%
Maximum Takeoff Weight (MTOW)	+18%	+3%	+11%	+10%
Range	-30%	+1%	-22%	+8%
Altitude	-36%	+22%	+9%	-27%
First flight	+ 8 months	+9 months	+9 months	+21 months
Type certification (Visual flight rules – VFR)	+11 months	+6 months	+12 months	+48 months
Type certification (Instrument flight rules – IFR)	+17 months	+8 months	+33 months	+48 months
Initial Delivery	+10 months	+8 months	+12 months	+44 months

A fundamental mass property in aircraft development is its empty weight, which should be reduced as much as possible. However, as indicated in Table 1, the empty weight of the four development projects analyzed by Andrew (2001) increased from 7% to 36% during the process (19% variation on average). This increase has negative impacts on other aircraft metrics, such lower payload, smaller range, or a reduction in altitude. It also affects many program metrics, leading to significant delays in all the major milestones.

Increases in weight usually follow a given pattern through the phases, as illustrated in Fig. 2. This figure shows a typical increase in aircraft weight during the development phases when a strong weight control strategy (approx. 5% weight increase in each stage) and a weak weight control strategy (approx. 12% weight increase in each stage) is adopted (Andrew 2001). This figure also illustrates Andrew's (2001) proposed strategy, called "Planned Value Profile" (PVP). In this strategy, the aircraft's target empty weight in the early stages of development (preliminary design) should be 5% lower than calculated to allow for an increase of 2% during the detailed design phase, 1% during the fabrication phase, and 2% during the testing phase. Thus, if the aircraft's weight meets the goal in all the development stages, its final weight will be the same as that initially specified. Andrew (2001) considered this strategy a significant contributing factor to enhance the success of weight control.

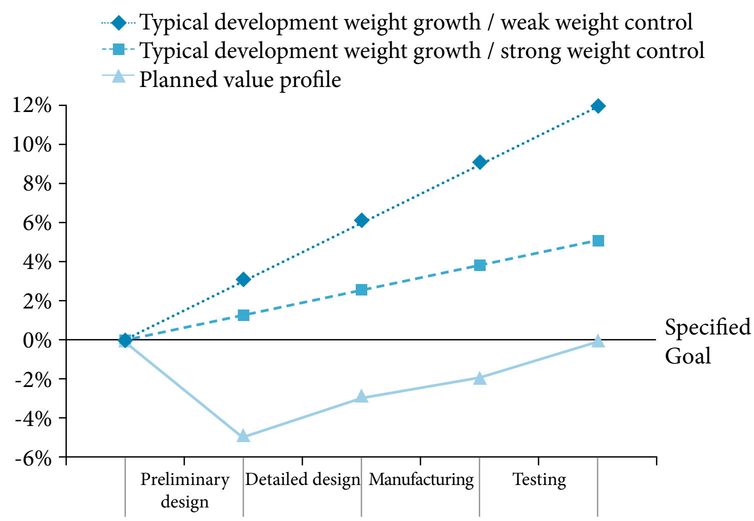


Figure 2. Planned Value Profile: Typical increase in weight during development is 12% (weak weight control) and 5% (strong weight control) (adapted from Andrew 2001).

Andrew (2001) stated that in typical development projects with strong weight control, the development team adopts a policy of "pound in/pound out mandate," i.e., a decrease in weight should compensate every increase in weight. In such projects, the team believes that the weight status reflects the overall soundness of an aircraft development program (Andrew 2001). However, the massive workload that has to be managed and shared, and that is concurrently performed by a large number of people, makes it challenging to ensure that the final aircraft has the same properties it had throughout the development process. The aircraft development process depends on the expertise, experience, and creativity of numerous people, who are often from different companies in the aircraft manufacturing value chain. The design approach currently in use is to compartmentalize subsystems and to break down the subsystem design tasks into discipline-specific tasks. This division is mainly driven by the need to share the workload (Hammond 2012). Hence, the path for solving challenges is to follow an integrated, effective, and efficient approach in aircraft development, known as systems engineering (SE).

SYSTEMS ENGINEERING, TECHNICAL INTEGRATION AND REQUIREMENT MANAGEMENT

Systems engineering (SE) is a holistic approach for product development that comprises several components and involves interaction among disciplines (INCOSE 2015). It has become a state-of-the-art methodology for organizing and managing aerospace production (Price *et al.* 2006).

A product is considered a system if it is composed of "a combination of interacting elements organized to achieve one or more stated purposes." Hammond (2012) states that the key to providing a product with quality is its development process, emphasizing that everything that exists is the result of a process. The ISO/IEC 15288 standard (ISO/IEC/IEEE 2008) specifies how the full life cycle of systems should be engineered, including conception, development, production, utilization, support, and retirement of systems. In this context, SE is "an interdisciplinary, collaborative approach that derives, evolves, and verifies a life-cycle balanced system solution" (INCOSE 2015).

The SE perspective deals with an inherent contradiction of the design process between specialization in disciplines and technologies – known as differentiation, and the need for integration – defined as the process of achieving unity of effort among various subsystems (Lawrence and Lorsch 1967). Technical integration is the fundamental element that pervades every aspect of aerospace system design, becoming increasingly concrete as the design process progresses through the various phases (Hammond 2012; Silva and Rozenfeld 2003). ISO/IEC 15288 describes technical integration as one of the main processes of the system life cycle, defining it as "a process that combines system elements to form complete or partial system configurations in order to create a product specified in the system requirements" (INCOSE 2015). However, technical integration requires a multidisciplinary approach to support the design process, and for participants to gain a better understanding of the relationship among systems and the analysis models generated during the design process (Price *et al.* 2006).

Due to the highly complex and integrated nature of modern aircraft systems, regulatory authorities have pointed out their concerns about the possibility of development errors causing or contributing to conditions that facilitate aircraft operational failures. The Aerospace Recommended Practice (ARP) 4754A (SAE 2010) proposes a methodology to address those concerns. It establishes levels of confidence for aircraft systems as a whole, presenting guidelines for the development of aircraft level, system level, and item level requirements. The process includes validating requirements and verifying if requirements are met, as well as configuration management and process assurance activities (SAE 2010). During most of the systems development, requirements and assumptions must be established based on hypotheses, since real information is not yet available, and this may lead to miscommunication about the basis and scope of assumptions, endangering the implementation of safety requirements. Therefore, assumptions should be identified, and their reasonableness and rationale should be established based on the specific system (SAE 2010).

The Society of Allied Weight Engineers – SAWE (2004) states that MPM is part of the overall systems engineering design process. The aircraft mass properties contain every part of the overall design. They define the locations of all those parts, how their mass affects the total design, and how their aggregation achieves and limits the goals of the design. The mass properties data must be continuously updated, always comparing the mass properties of the complete aircraft against the goals and limits of the design. Mass properties are assumptions made during the development process. These assumptions become a vital part of the overall system requirements package, and should therefore involve the same validation activities as those to which other requirements are subjected.

The aircraft and system development is iterative, concurrent, and subject to top-down and bottom-up influences (Rogers 2008; SAE 2010). According to the SAWE (2004), all the phases of the aircraft development process should be associated with an iterative MPM process that is scalable from the lowest design team level to the system level. The MPM process consists of eight subprocesses that interact with the SE, classified as "Management" or "Technical." These subprocesses are listed in Table 2.

The MPM process and SE should be better combined, with strong emphasis on integrating information across and through disciplines. A key factor to successful SE is an environment that embeds the development process – adequate communication across all disciplines is essential (Hammond 2012).

Table 2. Subprocesses that make up the iterative MPM process according to SAWE (2004).

Category	Subprocess
Management	Plan mass properties technical effort
Management	Manage mass properties risk
Management	Develop mass properties metrics
Management	Control mass properties baseline
Technical	Analyze mass properties requirements
Technical	Allocate mass properties requirements
Technical	Optimize mass properties
Technical	Verify and validate mass properties (analysis and measurement)

VALUE IN THE AIRCRAFT DEVELOPMENT PROCESS

This section focuses on the value, which is not a technical property of the aircraft but a subjective characteristic intrinsic to the client. This value reflects the commercial potential of a solution and justifies the customer's choices when acquiring it. The value of an entity (tangible or intangible) is defined as the benefits or worth that may be derived from it, considering its trade-off with the losses or sacrifices related to the entity (Reber *et al.* 2019; Shen *et al.* 2010; Slack 1998; Wang *et al.* 2014).

Value is a multidimensional attribute, and its dimensions are described differently by each author. Table 3 summarizes 98 dimensions that some authors consider when defining value. A detailed explanation of the table is given in the subsequent paragraphs:

Table 3. Dimensions considered by each author when describing "value" (Source: the authors).

Author	Dimensions of value
Reber *et al.* (2019)	Availability; Exchange worth; Cost; Price; Usefulness; Utility
Slack (1998)	Usefulness; Importance of satisfying the need; Availability; Cost of ownership
Collopy (2012), Collopy and Hollingsworth (2011)	Utility; Worth - (Measurable preference)
Murman *et al.* (2000)	Performance; Mission effectiveness; Purchase price; Affordability; Sustainability; Delivery time

Reber *et al.* (2019) state that the value of a generic entity (regardless of the field in which it operates) is commonly referred to in terms of availability, exchange worth, cost, price, usefulness, and utility.

In the aeronautical context, some authors also discuss the term value. Slack (1998), for example, states that value is a function of usefulness, the importance of satisfying the need, availability, and cost of ownership. For those who adopt value-driven design, value is seen from the perspective of utility or worth of a given entity, which should be quantifiable through value models so that the preference for one entity over another can be "measured" (Collopy 2012; Collopy and Hollingsworth 2011). From a broader standpoint, Murman *et al.* (2000) specify aircraft value in terms of performance, mission effectiveness, purchase price, affordability, sustainability, and delivery time.

All the terms employed by Murman *et al.* (2000) to describe aircraft value are directly linked with the mass properties of aircraft (Raymer 2012), which can be explained as follows. From the standpoint of commercial flight passengers, a basic need to be satisfied is to be able to travel long distances in the shortest possible time, preferably at low prices. The ability of the airplane to satisfy this need depends directly on the aircraft's performance (speed, range, and fuel consumption) and mission effectiveness. Aircraft performance and mission effectiveness can be affected by new technologies, such as new composite materials (Zhang *et al.* 2018), and by structural efficiency (Curran *et al.* 2004), both of which influence mass properties. At the same time, airlines seek to maximize their profits, which they can achieve by carrying more passengers and cargo at lower operating costs and an aircraft purchase price proportional to its functional worth (affordability) (Curran *et al.* 2004). An aircraft's purchase price is correlated with its empty weight (Liem *et al.* 2014). Its direct operating costs are a function of purchase price, fuel efficiency, maintenance, crew, navigation, and ground services (Curran *et al.* 2004), where fuel efficiency is also highly dependent on empty weight (Liem *et al.* 2014). Therefore, it can be stated that affordability directly correlates with the airplane's empty weight. The sustainability of an airplane is also directly related to its fuel efficiency (Gössling *et al.* 2007), and is also correlated with the aircraft's empty weight (Liem *et al.* 2014). Lastly, delivery time depends on the efficiency of the development process (Markham and Lee 2013), which may be hindered by excessive iterations due to ineffective control of mass properties.

The above discussion explains how the benefits that comprise the perceived value of an aircraft are highly dependent on its mass properties. Therefore, it can be assumed that if an effective MPM process positively impacts the aircraft's mass properties, the process will consequently also enhance its perceived value.

METHODOLOGY

As discussed in the introduction of this paper, we propose a concept to coordinate and improve the integration between the MPM and aircraft development processes. To this end, a methodology was employed that combines the following set of methods to achieve its goals:

- Literature review to systematize the theory on mass property management (MPM).
- An exploratory case study to compare practice and theory, and to highlight and confirm the limitations and relevance of this study.
- Inductive reasoning to summarize the characteristics of the MPM process integrated with aircraft development.
- A longitudinal participatory case study to define improvement projects.
- A technique for assessing the consensus of opinions from experts, validating the proposed projects based on a questionnaire.

Fig. 3 represents the general methodology of this project, which is explained in detail in the subsequent paragraphs:

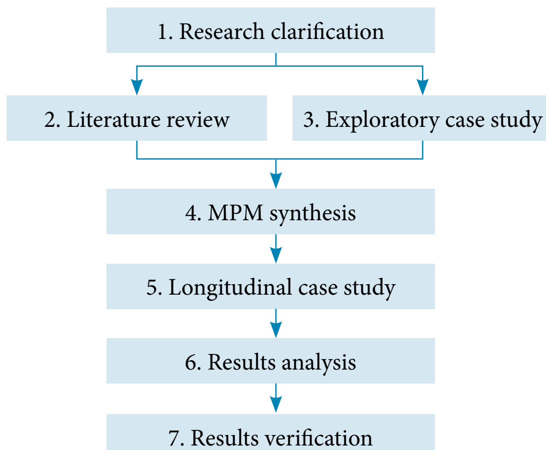


Figure 3. Research Methodology (Source: the authors).

Phase 1 identifies a meaningful problem and discusses the existing process and situation, as described in the Introduction of this paper. Phase 2 covers the identification of the main factors that influence the MPM, based on a literature review (Section "Mass Properties Management - Theory"). Phase 3 consists of an exploratory case study, also aimed at identifying the main factors that influence the MPM. One of the authors of this paper headed the MPM process in an aircraft development program for three years, employing as research instruments for this case study documentation analysis, participatory observation, logbook, and semi-structured interviews with major stakeholders of the development process (Subsection "Exploratory Case Study").

The results of Phase 2 and Phase 3 converged through inductive reasoning to a synthesis of the MPM characteristics (Subsection "Synthesis of MPM characteristics"), which covers Phase 4. The structure of this synthesis must be compatible with the goal of this study: the proposal of a concept to coordinate the integration between the MPM process and the aircraft development process. Therefore, the nature of those processes had to be evaluated in order to identify the most suitable structure. Both MPM and aircraft development are business processes, i.e., "the combination of a set of activities within an enterprise with a structure describing their logical order and dependence whose objective is to produce a desired result" (Aguilar-Savén 2004). This concept of business process replaces the classical functional view with a horizontal view, whereby the unit of analysis becomes a chain of activities and events (Silva and Rozenfeld 2003). Product development processes are a specific type of business process that involves creativity and innovation and is nonlinear and iterative. Although certain activities may be repeated, the desired overall result is unique, which characterizes each development as a project. According to Browning *et al.* (2006), process models support the integration of project system models and the effective management of projects. Therefore, we posit the hypothesis that a process model representing the main process perspectives would be an adequate structure to synthesize the MPM characteristics.

In addition, according to Silva and Rozenfeld (2003), the product development process consists of four dimensions, which should work hand in hand. The dimensions are as follows:

- Goal/strategy (involving portfolio management, performance evaluation, cross-functional relationships, and partnerships with suppliers);
- Activities/deliverables (set of specific operational activities performed in the product development process and the corresponding information involved);
- Resources/tools (techniques, methods, tools and systems used to support the performance of the activities aimed at achieving the stated goals/strategies);
- Organization/roles and responsibilities (involving the organizational structure and leadership, teamwork culture, and learning conditions).

Therefore, a synthesis of MPM characteristics was proposed considering the main dimensions of MPM: goal/strategy, activities/deliverables, resources/tools, and organization/roles and responsibilities (Phase 4, Subsection "Synthesis of MPM characteristics").

Phase 5 consists of a longitudinal participatory case study (Subsection "Longitudinal Case Study"), in which one of the authors participated in the MPM of an aircraft development project at an aircraft manufacturing company. The MPM synthesis from Phase 4 provided input for a protocol, which structured the longitudinal case study and defined the unit of analysis, following the guidelines proposed by Yin (2003). In Phase 6, the findings of the longitudinal case study were compared to the synthesis of MPM characteristics that resulted from Phase 4 (Subsection "Longitudinal Case Study"). The final analysis was structured in the form of a diagnosis, considering the main dimensions and characteristics of the process.

Lastly, the proposal of the integrated model and the improvement projects were presented in a workshop at the company and verified by experts using a structured questionnaire (Section "Verification of the proposal"). Based on the dimensions proposed by Vernadat (1996), we defined the evaluation criteria proposed in Table 4.

Table 4. Evaluation criteria proposed for the structured questionnaire employed to verify the proposal (adapted by the authors).

Evaluation criteria	Definition
Scope	Definition and clarification of the content under analysis, integrated model, improvement projects, and identification of border conditions.
Depth	Level of detail of the presented information.
Objectivity	Information precision, considering the goals of the analysis.
Comprehensiveness	Evaluation of the comprehensiveness of the application, considering the different development phases.
Utility	Problem identified concisely to contribute to the effectiveness of the solution.
Simplicity and clarity	It is easy for users to understand.
Consistency	Information compatibility and adherence.

The results obtained from the questionnaire were analyzed based on the average and the inter-rater reliability (IRR) index of the scores assigned to each of the questions asked (Section "Verification of the proposal"). The IRR was employed to analyze the reliability of the input from the different specialists. The purpose of the IRR is to verify the degree of "interchangeability" of experts by measuring the level of agreement of a set of notes. This index may vary from zero to one, with "one" indicating complete homogeneity of the respondents' opinions and "zero" indicating complete heterogeneity of their opinions (James *et al.* 1984).

The IRR can be calculated using Eq. 1:

$$IRR=1-S_j^2/\sigma_j^2 \tag{1}$$

where j is the number of respondents, S is the observed standard deviation, and σ is the deviation expected when all the opinions are random. The expected standard deviation can be determined by Eq. 2:

$$\sigma_j^2=(A^2-1)/12 \tag{2}$$

where A is the number of alternatives on the score scale. Eq. 2 assumes that each question is distributed uniformly (James *et al.* 1984).

CASE STUDIES, SYNTHESIS, AND PRACTICES

This section discusses the results obtained from the proposed methodology. The first subsection describes the exploratory case study conducted to collect evidence for the MPM characteristics. The second subsection contains a table synthesizing the MPM characteristics derived from the literature and the exploratory case study, establishing how those characteristics are integrated into the aircraft development process. Lastly, the third subsection describes the longitudinal case study, from which practices were extracted to improve the integration between the aircraft development process and MPM.

EXPLORATORY CASE STUDY

To help understand MPM within the aircraft development process and to compare it to the theory, an exploratory case study was conducted at a major airplane manufacturing company that is a market leader. The company is engaged in various development projects that are currently in different phases of development, which was a valuable factor contributing to this research. During the exploratory case study, we conducted semi-structured interviews with company employees from different areas/disciplines and distinct hierarchical positions, whose responses contributed to the formulation of a summary of the main MPM characteristics.

This study used multiple sources of evidence collected over a three-year period, such as documentation, observation, and logbooks. The results were structured based on the main dimensions of the process and the development phases proposed by Torenbeek (2013) (Subsection "Aircraft Development Process and MPM"). The findings of the exploratory case study clarified MPM characteristics and also provided input for defining the model characteristics. These results are presented in the Subsection "Synthesis of MPM characteristics."

SYNTHESIS OF MPM CHARACTERISTICS

A set of characteristics was proposed for each of the four main dimensions of MPM (Section "Methodology") to define the relationship between MPM and aircraft development jointly. These characteristics describe the MPM features and are the central part of the conceptual model proposed in this paper. The MPM characteristics are listed in four tables (Tables 5, 6, 7, and 8), each of which is related to a distinct dimension ("Goals/Strategy," "Activities/Information," "Resources/Tools," and "Organization/Roles and Responsibilities," respectively). Each characteristic is related to the reference that originated it (literature references and/or exploratory case study) and its definition.

Table 5. Synthesis MPM characteristics in the dimension of "Goals/Strategy" (Source: the authors).

Characteristic	References	Definition
Target Weight for each phase (strategies such as Planned Value Profile (PVP)	(Andrew 2001, SAWE 2004), Exploratory Case Study	Establishing a target weight for aircraft in each phase, which should not be exceeded. This is an essential characteristic of MPM. This target is based on former product generations or a reference product. It should be noted that it determines the maximum allowed value. However, weight may vary between the maximum target weight and the minimum potential weight (see "Opportunities and risk monitoring to have a probabilistic value").
Local target weight	(Heim and Pertermann 2008, SAWE 2004), Exploratory Case Study	Establishment of a target weight for each aircraft system, subsystem, or part. This is an essential characteristic of MPM. This target derives from former product generations or a reference product, and it determines a maximum allowed value. However, local weight may also vary between a maximum target weight and the minimum potential weight.
Leadership support	(Andrew 2001, SAWE 2018), Exploratory Case Study	Involving and engaging the leadership for the success of the MPM process. This is an essential characteristic of MPM.
Weight information in trade-offs	(Murman *et al.* 2000, SAWE 2004), Case Study	Evaluating how much impact derives from MPM information when compared to cost and schedule in the decision-making process.

Table 6. Synthesis of MPM characteristics in the dimension of "Activities/Information" (Source: the authors).

Characteristic	References	Definition
Weight estimation is critical	(Andrew 2001, Raymer 2012, SAWE 2004, 2018), Exploratory Case Study	Determining whether weight estimation is considered a core activity in the company and should be present in conceptual design and preliminary design phases. This is considered a crucial characteristic of MPM.
Weight subprocess categories	(ISO/IEC/IEEE 2008, SAWE 2004), Exploratory Case Study	This characteristic is related to the classification of MPM activities in the organization. These activities are present in each product development phase and can be classified as technical, management, or integrative.
Weight Saving Award	(SAWE 2004)	The activity of identifying all the parts involved in the project due to weight saving during detailed design and later phases.

Table 7. Synthesis of MPM characteristics in the dimension of "Resources/Tools" (Source: the authors).

Characteristic	References	Definition
Methods and tools for calculation in each development phase	(Price *et al.* 2006), Exploratory Case Study	There are specific methods and tools for calculating mass properties in each phase of development (e.g., mathematical estimations for conceptual design, and CAD for detailed design). This characteristic evaluates the manufacturer's adaptability and the quality of calculation.
Integrated mass properties database	(Dahm 2007), Exploratory Case Study	Use of a data management module for mass properties with controlled access, multiple users, and adequate response time. Essential to ensure data quality in all the development phases.
Integration among database/ CAD/DMU	(Price *et al.* 2006), Exploratory Case Study	Mass properties management and control in the CAD and DMU environment. An essential characteristic in all the development phases.
Opportunities and risk monitoring to have a probabilistic value	(Dahm 2007), Exploratory Case Study	Information maturity does not evolve homogeneously during product development. Therefore, weight and other mass properties should be seen as probabilistic values. This is essential to ensure data quality in all the development phases.
Automated weight status visibility	(Dahm 2007)	The databases should be integrated for automated weight status visibility during all the development phases.
Integrated engineering change management with mass properties information	(ISO/IEC/IEEE 2008, SAWE 2004)	Integration of the change management process and mass properties information, protecting the integrity and availability of information. This is essential to ensure data quality in all the development phases.

Fig. 4 shows an overview of the integration of the MPM process characteristics and the aircraft development process. This overview is structured based on the typical dimensions of a process model (indicated by dashed rectangles): activities/information, resources/tools, goals/strategy, and organization/roles and responsibilities. Each rectangle under the aircraft development process phases represents the main characteristics identified here. The length and position from each rectangle are associated with the phases (upper part of the figure) of the aircraft development process to which they are linked (e.g., the characteristic of "weight estimation is critical" is connected with the conceptual design and the beginning of the preliminary design phases). Note the overlap of the development process phases, as can be seen in Fig. 1. This overlap was omitted in Fig. 4 to facilitate the interpretation of the image, but the overlap between phases must be kept in mind. The characteristics of resources/tools were divided into three groups: "quality database" (identified inside the light grey rectangle), integration (identified by each arrow), and methods and tools for each phase. The rectangles in the lower part of the figure indicate the variables of organization/roles and responsibilities, indicating that they should be considered as part of the whole development process and embedded in the organization.

Table 8. Synthesis of MPM characteristics in the dimension of "Organization/Roles and Responsibilities" (Source: the authors).

Characteristic	References	Definition
Technical integration	(Hammond 2012, SAWE 2018), Exploratory Case Study	Ensuring that the effectiveness of information exchange among groups in different fields of expertise and the integration of all different outputs from each group meets the requirements. This includes the formal existence of this role in the organization. Thus, it is essential to MPM, and an essential characteristic in all the development phases.
MPM: a shared responsibility	(Raymer 2012, SAWE 2004), Exploratory Case Study	The ability of everyone involved in the product development to continually analyze and update the mass properties. Continuous evaluation of the MPM workload distribution among designers, engineers, and managers. This characteristic is essential in all the development phases.
Aviation Culture	(SAWE 2004), Exploratory Case Study	Determines whether the MPM is entitled to request changes and drive design. This characteristic is essential in all the development phases.
Use of new technologies	(Dahm 2007, Dray 2013)	Evaluation of the level of application of new technologies in the product. A positive relationship was identified between the characteristic "use of new technologies" and MPM, and was found to be more present from the beginning of the development up to the detailed design phase.

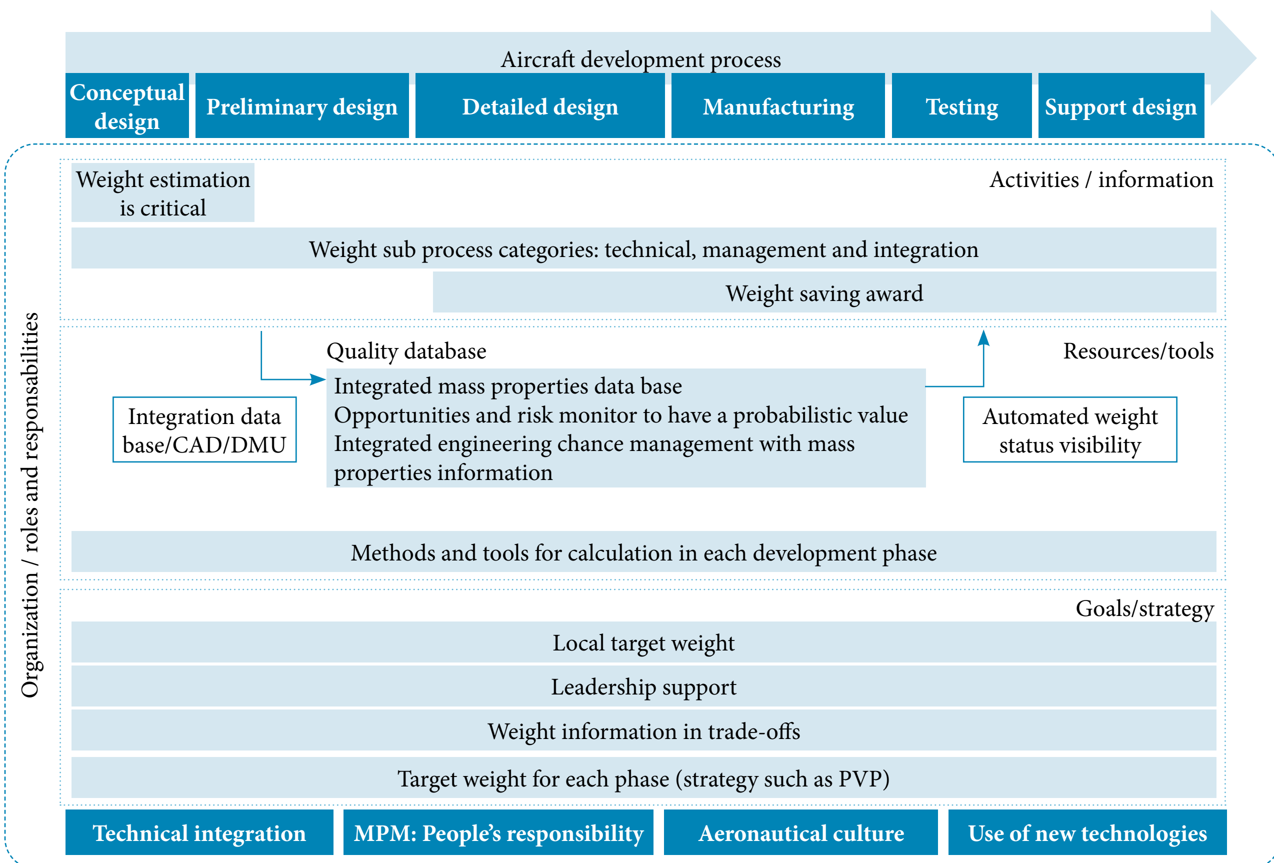


Figure 4. Coordination of the MPM process and aircraft development process (Source: the authors).

LONGITUDINAL CASE STUDY

We conducted a 12-month longitudinal case study, as described in the Section "Methodology." The dimensions and characteristics of the integration depicted in Fig. 4 influenced the design of the case study. Moreover, the case study was structured based on a protocol to measure the evidence of the characteristics, establishing potential values that each variable could assume. The protocol was derived from the synthesis of the MPM characteristics (see Tables 5, 6, 7, and 8). In this protocol, we established the variables that could be used to measure each characteristic, which values those variables could assume, and which question should be posed to measure this variable. An excerpt from this protocol is given in Table 9 as an example.

Table 9. Synthesis of the characteristics of MPM (Source: the authors).

Objective	Characteristic	Variable (how to measure the characteristics)	Possible assumed values	Question
Analyze goals/ strategy dimension	Target weight for each phase	Existence of a target weight strategy in each development phase	Yes	Does the company use a target weight implementation strategy depending on all the development phases?
			No	
	Local target weight	Existence of a local target weight for every development phase	Yes	Is there a target weight allocation at the lowest possible level in all the development phases?
			No	
	Leadership support	Existence of guidelines for the development: "pound-in pound-out" mandate	Yes	Has the company adopted a policy of "pound-in-pound-out" mandate?
			No	
	Weight information in trade-offs	Scale pertaining to the weighting of mass properties information in trade-offs when compared to time and cost	Higher than cost and time	Is the MPM information in trade-offs as important as time and cost?
			Higher than cost only	
			Higher than time only	
			Lower than cost and time	

Although the longitudinal case study was conducted at the same manufacturer as the exploratory case study, the main objective of the longitudinal case study was to make an in-depth comparison of its findings with the proposed integration of the MPM process and aircraft development. Discrepancies between MPM characteristics and the integration of MPM and aircraft development were analyzed jointly by the research team and stakeholders, aiming to propose and plan practices to coordinate the integration of the two processes in a transparent way for the participants of a new aircraft program. The evidence from this case study came from different data sources: document analysis, historical records, interviews, and participant observation. This diversity of data sources allowed for data triangulation (Yin 2003).

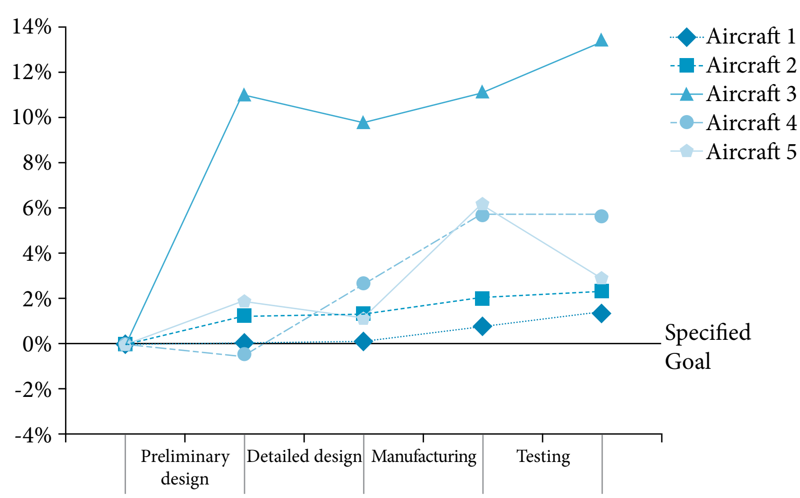
To understand the context of the company, we offer a few qualitative comments regarding the longitudinal case study. In this company, the MPM process is not expressed explicitly in any of the product development model guidelines. However, the MPM process pertains to supplier management and selection, tools, business plan, risk management, requirements management, and product development management.

According to our observations and feedback from interviews, the company engages in MPM throughout the phases of the product development process. Furthermore, the company was working on ongoing development projects during the period of this study. We found that the company had a reference model for structuring the product development process, which is documented according to business standards and is followed in all the company's product development projects. However, the company does not have a reference model to support MPM activities. There is no record of documents that explicitly discuss the product development process and the MPM activities for the development phases. Some documents provide implicit connections between both processes in the phases of conceptual design, preliminary design, detailed design, manufacturing, and testing. But there is no documentation indicating this relationship in the support design phase, even if only implicitly.

The interviewees were unanimous in stating that everyone involved in the product development process is also connected to the MPM process. However, there is no documentary evidence linking their fields of expertise with MPM. The company has a specific department officially responsible for aircraft mass properties. This department is functionally connected to the engineering management level, which assigns one MPM team to each product development project. The MPM team is active in all the phases of product development, except for the conceptual design phase, which is characterized by intense interactions among groups in different fields of expertise.

Fig. 5 illustrates the performance of the MPM process in the company, indicating the increase in empty weight of five different aircraft under development, showing the percent variation of the empty weight initially specified in the conceptual design phase (0%) to the aircraft's empty weight upon entry into service. As can be seen, the company's MPM process produces different results, depending on the degree of novelty of the aircraft under development. Aircraft 1 and 2 are incremental development projects based on products that are already operating in the company's portfolio. The weight deviation of these airplanes was lower than 3%. In contrast, aircraft 3 and 4 are innovative development projects, presenting deviations higher than 5% (about 14% and 6%, respectively). The interviewees also highlighted this aspect, pointing out that innovative development projects should allow more significant deviations in mass properties.

One aspect regarding aircraft 5 should be pointed out, namely, the fact that the variation in its empty weight between the manufacturing and testing phases was significantly reduced. This drop in the final development phases was only possible due to an intense effort to reduce the empty weight and ensure the desired product performance. The performance of aircraft 5 was critical, leading to a delay of a few months in the development project, so the empty weight variation was lower than 3%.



phases (Source: the authors).

Figure 5. Aircraft percent deviation from initial empty weight throughout the development

From an overall standpoint, the research team considered that the company would benefit from keeping better records of the relationship between the aircraft development process and MPM. Such records are needed, since employees are tacitly aware of this relationship but it is not explicit. Furthermore, a comparison of the company structure and the synthesis of MPM characteristics revealed other gaps in the manufacturer's current MPM process. These gaps correspond to sixteen practices that should help the company improve the integration between the aircraft development process and the MPM process. Improvement projects were outlined to implement the proposed practices, which will serve as a roadmap for the company to coordinate the integration between its MPM and aircraft development processes, with each proposition to be considered a step towards improvement. Table 10 describes those practices, which are grouped by dimension and represent the key output of this paper.

Table 10. Main practices for improving integration between aircraft development and MPM processes (Source: the authors).

Dimension	Main practices
Goals/Strategy	1) Increase awareness of the target weight in the strategy development phase 2) Increase the allocation of local target weights in all the development phases 3) Establish the correlation between MPM and value to the customer
Activities/ Information	4) Increase the number of people involved in the weight estimation activity: a core activity. 5) Include the savings award activity in the company's MPM process 6) Enhance the relationship between MPM and supply chain
Resources/Tools	7) Create an integrated mass properties database 8) Develop an automated tool for updating the MPM database 9) Increase the homogeneity of MPM tools within the company 10) Weight visibility should consider that information is probabilistic 11) Create tools that generate automatic online weight visibility 12) Enhance the relationship between MPM and engineering change management
Organization/ Roles and Responsibilities	13) Document roles and responsibilities in MPM 14) Increase the relationship between technical integration and MPM 15) Heighten awareness about the importance of MPM among those involved in the development process 16) Increase the exchange of information among departments in order to increase the use of new weight saving technologies

To explain how the improvement projects were based on the gaps, an example is given here of the characteristic "integrated mass properties database" of the resources/tools dimension. During the case study, we found that the company keeps only mass information in the database. Other types of MPM information (such as center of gravity and products and moments of inertia) are controlled in several non-integrated worksheets. Therefore, we propose that the company adopt item (7) of Table 10 as an improvement project.

Note that these improvement projects were proposed in the specific context of this aircraft manufacturing company. However, they can also be considered as suggested practices for other aircraft developers in the context of the integration of their MPM and product development processes.

VERIFICATION OF THE PROPOSAL

The proposed integration between MPM and aircraft development processes (Fig. 4), as well as the suggested improvement projects, were evaluated using the questionnaire described in the section "Methodology". Our analysis and proposed improvement projects were presented to a group of thirteen experts at the company, comprising engineers, technicians, and managers of different development programs. This presentation was given during a 2-hour workshop. The group filled out the questionnaire, providing answers regarding the analysis criteria. As explained in the methodology section, the answers were evaluated based on the IRR index, which measures the level of consensus of a set of scores. The results are presented in Table 11. The evaluation criteria were already discussed in the section "Methodology."

The overall average of the evaluations was 83%, which corresponds to the median value between the standard answers "satisfied (75%)"and "extremely satisfied (100%)". All criteria had an average higher than 75%, and the IRR of each criterion was higher than 0.5, indicating agreement among the answers. The criterion with the lowest average was consistency. This may be explained based on the comments elicited during the interview. As mentioned earlier herein, this presentation was given during a 2-hour workshop. Therefore, due to the very brief time available, our presentation focused on the practices rather than on a step by step explanation of the research work. As a result, some of the interviewees stated that because of the brevity of this presentation, they had failed to grasp some of the points. The criterion with the highest average was objectivity, indicating that the accuracy of information was high, considering the purpose of the analysis.

Table 11. Verification of the answers to the questionnaire based on the IRR. (Source: the authors).

Criteria	Average	IRR
Scope	87%	0.63
Depth	77%	0.8
Objectivity	90%	0.64
Comprehensiveness of use	81%	0.68
Usefulness	87%	0.63
Simplicity and Clarity	87%	0.52
Consistency	75%	0.71

CONCLUSIONS

In this paper, the process of MPM was analyzed considering its main dimensions, i.e., strategies/goals, activities/deliverables, resources/tools, and organization/roles and responsibilities. The main characteristics of these dimensions derive from the synthesis of MPM characteristics garnered from the literature review, which served as the basis for conducting a case study at an aircraft manufacturing company. Lastly, this paper proposed sixteen practices aimed at enhancing the integration between the aircraft development process and MPM. These practices cannot be generalized, since they are based on a specific case study. However, this case study was conducted at a world-class aircraft manufacturer, whose stated problems and limitations in integrating its MPM and aircraft development process were in consonance with the findings garnered in our literature research. Therefore, the sixteen practices can be considered an initial version of good practices to coordinate the integration of MPM and aircraft development processes.

A group of experts from the company evaluated and verified the recommendations of this study, and expressed their "satisfaction" or "extreme satisfaction" with the results of this work. In this analysis, the criteria that received the best evaluation were *objectivity*, *scope*, and *usefulness*, which confirms the positive contribution of this research to the practitioners, since it solved a significant challenge in the industry problem. This allows us to state that we have successfully met the goal of proposing a concept to coordinate the integration between the MPM and aircraft development processes.

The main contribution of this work to the theory is the proposal of the coordinated integration of the MPM and aircraft development process. Practitioners may use this case study to replicate this procedure in their organization, considering the proposed practices. Companies in other fields of transportation that also build vehicles (Boze and Hester 2009), such as the automotive industry (Stegmiller *et al.* 2018), may also be inspired by the techniques proposed herein. Furthermore, as explained in the subsection "Value in the aircraft development process," the use of a more effective and integrated MPM process may enhance the aircraft's perceived value and reduce the airplane's environmental impact during its life cycle, since its impact is tied to fuel efficiency (Gössling *et al.* 2007), which in turn is correlated with its empty weight (Liem *et al.* 2014)

As further contributions to the theory, this paper summarizes the body of knowledge about how MPM, customer value, SE standards (INCOSE 2015, ISO/IEC/IEEE 2008), and the ARP4754A (SAE 2010) are connected. The approach of this research also offers a broader view of the MPM process than that proposed in the literature (Dahm 2007; Raymer 2012; SAWE 2004, 2018).

A major limitation of this study is the fact that the outcomes of the proposed practices were not validated through practical application. However, the benefits of these practices may be evaluated as a continuation of this work.

The aspect that distinguishes this work from other publications in the literature is its holistic and integrated approach in analyzing the MPM process and comparing it with the theory, as well as providing results based on a concrete case study conducted at a world-class aircraft manufacturing company.

The MPM process, while still under-researched, is essential for the success of aircraft development processes. The efficiency of the MPM process directly influences the perceived value of an aircraft, impacting its commercial potential and its market competitiveness. Measuring the effective impact of each practice on the performance in managing mass properties, for example, could contribute to the creation of a knowledge base for selecting the practices that contribute the most to MPM effectiveness. The authors therefore suggest that further research in this field be considered and conducted.

AUTHOR'S CONTRIBUTION

Conceptualization: Paula V and Rozenfeld H; Methodology: Paula V and Rozenfeld H; Investigation: Paula V; Writing – Original Draft: Paula V and Rosa M; Writing – Review & Editing: Paula V; Rosa M and Rozenfeld H; Funding Acquisition: Paula V and Rozenfeld H; Resources: Paula V and Rozenfeld H; Supervision: Rozenfeld H.

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