

## PROPOSAL FOR COMBINING AGENT-BASED MODELS DEVELOPMENT WITH PROBLEM STRUCTURING METHODS FOR AIRCRAFT CONDITION-BASED MAINTENANCE

*PROPOSTA DE COMBINAÇÃO DO DESENVOLVIMENTO DE MODELOS BASEADOS EM AGENTES COM  
MÉTODOS DE ESTRUTURAÇÃO DE PROBLEMAS PARA A MANUTENÇÃO BASEADA NA CONDIÇÃO*

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### **Abstract**

The aircraft maintenance is a complex system and there is a trend for shifting from pre-determined maintenance to Condition-based Maintenance (CBM). The use of modeling and simulation is an alternative in this scenario where there is a need for decision support from strategic to operational aspects. Agent-based Modeling (ABM), that is a bottom-up modeling approach centered in agents, can be an alternative in the simulation of complex systems. However, given a situation with multiple stakeholders, multiple perspectives, intangible aspects and relevant uncertainties, methods that support the problem structuring are necessary. Problem Structuring Methods (PSM) and facilitated modeling can improve the stakeholder's engagement and can provide a clearer vision of the problem that the model will address. This work proposes a model for combining PSMs with ABM for an aircraft CBM application. The proposed multimethodology model use case partial results show that it can improve the stakeholder's engagement and the definition of the goals and boundaries of the ABM model.

Keywords: Agent-based Modeling, Problem Structuring Methods, Multimethodology.

## Resumo

A manutenção de aeronaves é um sistema complexo e há uma tendência de mudança das manutenções pré-determinadas para a Manutenção baseada na Condição (MBC). O uso de modelagem e simulação pode ser uma alternativa nesse cenário onde há a necessidade de suporte a decisão para aspectos que vão do estratégico ao operacional. A Modelagem baseada em Agentes (MBA), que é uma abordagem de modelagem bottom-up centrada em agentes, pode ser uma alternativa para a simulação de sistemas complexos. No entanto, dado o cenário de manutenção aeronáutica com múltiplos interessados, diferentes perspectivas, aspectos intangíveis e incertezas relevantes, métodos para suportar o processo de estruturação do problema são necessários. Métodos de Estruturação de Problemas (MEPs) e a modelagem facilitada podem aprimorar o engajamento dos interessados assim como prover uma visão mais clara do problema para o qual o modelo será desenvolvido. Este trabalho propõe um método para a combinação de MEPs e a MBA para uma aplicação na MBC de aeronaves. Os resultados parciais do estudo de caso mostram que o modelo multimetodológico proposto auxilia no engajamento dos interessados assim como na definição dos objetivos e das fronteiras do modelo baseado em agentes.

**Palavras-chave:** Modelagem baseada em Agentes, Métodos de Estruturação de Problemas, Multimetodologia.

## INTRODUCTION

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The maintenance can be divided into corrective, preventive and predictive (EN13306, 2010). Corrective maintenance can be subdivided into immediate corrective maintenance, in which work starts immediately after a failure, and deferred corrective maintenance, in which work is delayed in conformance to a given set of maintenance rules. The preventive maintenance is carried out

at predetermined intervals or according to prescribed criteria and is intended to reduce the probability of failure or the degradation of an item function. One type of preventive maintenance is the predetermined, where the tasks are performed according to fixed time intervals or according to a utilization metric such as number of flight hours. The other type of preventive maintenance is the condition-based that is a maintenance strategy based on the asset's condition identified through direct or indirect monitoring (SAE JA6097, 2019). CBM requires specific knowledge of an asset's condition at any given time in its operating life such that the maintenance action can be planned with enough lead time. CBM differs from 'on-condition' maintenance in that it requires knowledge of the asset condition at any given time, what provides an understanding of how much time is available before the required maintenance must be performed (SAE JA6097, 2019).

Modeling and simulation are often used for decision support in the different layers of the condition-based maintenance, for example for predicting when the failures will occur or the best maintenance date according to the aircraft health condition (HOLZEL et al., 2014; LEE; MITICI, 2020).

Multimethodologies and mixed methods are a way to combine two or more methodologies, techniques, or tools for dealing with the real-world complex and multi-dimensional problems. (MINGERS; BROCKLESBY, 1997; JOHNSON et al., 2007; POLLACK, 2009). The benefits of mixing methods include the combination of quantitative and qualitative re-search strengths, stronger evidence for a conclusion through convergence of findings, more confidence in the results and exploration of insights that might be missing when a single method is used (HOWICK; ACKERMANN, 2011; JOHNSON; ONWUEGBUZIE, 2004). Dyson et al. (2021) shows that soft Operations Research (OR) and hard OR can benefit from each other instead of being considered as separated fields by the OR practitioners.

Wicked situations, where mixed methods can be used and where some condition-based maintenance problems can fit, are characterized as changing over time, having a high degree of uncertainty and conflicting positions of the stakeholders (RITTEL; WEBBER, 1973).

In Operations Research and Management Sciences (OR/MS), PSMs are a set of methods that were developed for tackling ill-structured problems with the following characteristics: multiple actors, multiple perspectives, incommensurable and/or conflicting interests, important intangibles and key uncertainties (MINGERS; ROSENHEAD, 2004). They are a group of model-based problem handling approaches whose purpose is to assist in the structuring of problems rather than directly to derive a solution (ROSENHEAD, 2013). Examples of the PSMs in action are the use of Soft Systems Methodology to develop a simulation of outpatient services (LEHANEY; PAUL, 1994) and the development of an information technology strategy for a supermarket chain with many areas involved and where multiple methodologies were mixed (MINGERS; ROSENHEAD, 2004).

The PSMs were developed in a context of increasing limitations experienced with traditional quantitative OR methods, as noted by Ackoff (1979), that describes the "increasing inappropriateness of OR's methodology". The most known PSM methods are (MINGERS; ROSENHEAD, 2004; ACKERMANN, 2012): Soft-Systems Methodology (SSM) (CHECKLAND, 1981), Strategic Objective Development and Analysis (SODA) (EDEN; ACKERMANN, 2001), Strategic Choice Approach (SCA) (FRIEND; HICKLING, 1997), Robustness Analysis (ROSENHEAD, 2001) and Drama Theory (BRYANT, 1997).

PSMs can be combined with techniques and tools according to the problem characteristics. Howick and Ackermann (2011) & Munro and Mingers (2002) show that PSMs are combined in many ways such as the mix of cognitive mapping with system dynamics, where the first is developed in group and further deployed into system dynamics models. Other example is the mix of SSM with

simulation, where first was used for supporting the problem definition.

Regarding modeling and simulation, Borshchev and Filippov (2004) describes four main types of techniques: System Dynamics (SD), Discrete-Event Simulation (DES), Agent-Based Modeling (ABM) and Dynamic Systems (DS). More specifically, ABM is a computational approach for modelling complex systems. In ABM, elements are agents with specific characteristics that interact according to precise rules, and whose characteristics or behaviors may be altered by these interactions. The outcomes of these interactions are monitored (MACAL; NORTH, 2010). ABM is used in a variety of applications, such as social sciences, economy (BARBATI et al., 2012), logistics optimization, biology, and urban planning (BANDINI et al., 2009). One example is the use of ABM for modeling and simulating practical supply chain management problems, where analytic or optimization methods cannot be used or global information sharing and central coordination are difficult to achieve (BARBATI et al., 2012). ABM is also associated with the simulation of sociotechnical systems where real experiments with different scenarios is not possible to be accomplished (BANDINI et al., 2009).

More specifically in CBM, there are works that uses modeling and simulation, for example to evaluate CBM against Time-based Maintenance (TBM) (KIM et al., 2016) or to evaluate the cost-benefit of using failure prognostics in an aircraft fleet (HOLZE et al., 2014).

As mentioned above, one technique that is suitable to be used with PSMs is modeling and simulation (MINGERS; BROCKLESBY, 1997). The use of computational models to simulate complex situations with multiple stakeholders can be addressed by facilitated or group modeling, where PSMs can be applied for problem structuring and definition. Franco and Montibeller (2010), Robinson et al. (2014) describes facilitated modeling as being consistent with PSMs, which can provide systemic view and stakeholders engagement to the simulation project.

There are examples of problem structuring methods with modeling and simulation in the literature. Smith and Shaw (2019) characterize the pillars of the PSMs and shows how discrete event simulation and system dynamics are related to these pillars, which are described in Section 4. Eden (1994) shows the integration between cognitive maps and system dynamics. Tako and Kotiadis (2015) proposes a framework that integrates SSM and discrete events simulations in healthcare.

The problem definition for complex simulation projects demands stakeholders' involvement, systemic view and the situation modeling (ROBINSON et al., 2014; VOINOV; BOUSQUET, 2010). These are pillars of the PSMs (SMITH; SHAW, 2019) and they can support a more effective computational modeling process. Another important feature of PSMs in comparison to other participative methods is the use of models as 'transitional objects' to structure stakeholders' engagement and to provide a focus for dialogue (MIDGLEY et al., 2013). PSMs also manages process and content, supporting a group's negotiation towards and agreed outcome (ACKERMANN, 2012).

More specifically, the integration of agent-based modeling with SSM is described in Novani and Mayangsari (2017), where the ABM is used as part of the root definitions and in the model comparison with reality. Elsayah et al. (2015) shows the process from cognitive maps elaboration to agent-based modeling. Ramanath and Gilbert (2004) describes the design of participatory agent-based social simulations.

The mix of agent-based modeling with other qualitative methods are described in Tubaro and Casilli (2010) and Saetra (2017). Group agent-models building is also part of the literature such as the one described in Taylor et al. (2016).

The combination of ABM and PSMs also contributes to one of the challenges for the evolution of the PSM field described by (ACKERMANN, 2012) that is the development of effective procedures for mixing methods.

The recent trends regarding the use of ABM in the OR field (MALERE; BELDERRAIN) shows that this simulation approach is used in many OR sub-areas such as transportation research and supply-chain management. It is also used in association with techniques that are part of PSMs (such as cognitive maps) and with group decision making.

The use of ABM can be an alternative to address problems in the complex aircraft maintenance system and the modeling process, due to the messy situations in this domain, requires stakeholders participatory methods, where PSMs can be an option, since these methods use 'transitional objects' to structure stakeholders engagement and to provide a focus for dialogue (MIDGLEY et al., 2013) and also manages process and content, supporting a group's negotiation towards and agreed outcome (ACKERMANN, 2012).

Given the need of developing a decision support tool that consists of agent-based simulation to be used in the complex maintenance system, this work proposes a multimethodology model for combining PSMs with ABM for an aircraft CBM application.

The remaining of the paper is organized as follows. Section 2 introduces the theoretical background that is relevant for the current work, including problem structuring methods, agent-based modeling and multimethodologies. Section 3 describes the proposed multimethodology model. Section 4 describes the CBM case study that is used for testing the proposed model and shows the results. Section 5 provides some discussion about the results and concludes the paper.

## THEORETICAL BACKGROUND

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This section brings a brief introduction to the theory that supports the proposed model and that includes problem structuring methods, facilitated modeling, agent-based modeling and multimethodology.

## Problem Structuring Methods

Problem Structuring Methods (PSMs) are a set of methods that were developed for tackling ill-structured problems with the following characteristics: multiple actors, multiple perspectives, incommensurable and/or conflicting interests, important intangibles, and key uncertainties (MINGERS; ROSENHEAD, 2004), for example organizational strategy definition and urban mobility problems. These methods were developed in a context of increasing limitations experienced with traditional quantitative OR methods, as noted by Ackoff (1979), that describes the "increasing inappropriateness of OR's methodology".

The most known PSM methods are (MINGERS; ROSENHEAD, 2004; ACKERMANN, 2012): Soft-Systems Methodology (SSM) (CHECKLAND, 1981), Strategic Objective Development and Analysis (SODA) (EDEN; ACKERMANN, 2001), Strategic Choice Approach (SCA) (FRIEND; HICKLING, 1997), Robustness Analysis (ROSENHEAD, 2001) and Drama Theory (BRYANT, 1997). Examples of wicked problems that are addressed in the literature include organizational restructuring and strategy development (MINGERS; ROSENHEAD, 2004).

The PSMs have many common and shared characteristics even though they were created separately. Rosenhead (1989) is an important work that brings some approaches that tackle messy problems under the umbrella of PSMs.

A general description of an intervention process, that in this work is assumed also to be the generic PSMs phases, is provided by Mingers and Brocklesby (1997). The definition of the PSMs pillars is proposed by Smith and Shaw (2019), that represents the characteristics that a method must have to be considered a PSM.

The intervention process defined by Mingers and Brocklesby (1997) is divided in four phases based on the abstraction of the SSM stages:

- **Appreciation:** this phase is mainly related to data production and initial identification of the problem to be structured with its associated

restrictions and limits. Here interviews, observation and meetings with stakeholders are performed

- **Analysis:** as the name implies this phase contains the analysis of the retrieved information and further understanding of the cause-and-effect relationships.
- **Assessment:** evaluates how the situation could be different from what it currently is and changes mechanisms are explored.
- **Action:** here actions that address the problematic situation are defined.

This intervention process is affected by three 'worlds': one material of the objective world that we observe; a personal world mainly subjective of what we believe and experience and a social world where ideas are shared and there is intersubjectivity.

Other important characterization of PSMs is in terms of their main pillars. Smith and Shaw (2019) define four characteristics of a PSM:

- **Systems characteristics:** is related to the model building process that identifies a system to a model, encouraging holistic understanding and that seeks to include in the model the participants subjective view of the world.
- **Knowledge and involvement of stakeholders:** this pillar includes the need of qualitative models that involve the facilitation of the participants and the knowledge sharing between them, developing buy-in to politically feasible outcomes.
- **Values of model building:** this pillar refers to the required model characteristics such as credibility and confidence.
- **Structured analysis:** describes how different stages of analysis are required for a PSM.

The PSMs pillars are based on the theoretical constructs of ontology, epistemology, axiology and research methodology and also in the paradigm theory from Guba and Lincoln (1994).

Another view of the problem structuring process is provided by (GEORGIU, 2010) where the information collection, model development &

verification and the problem definition are performed with the ultimate decision makers prior to the decision for action. The more traditional hard OR approach emphasizes more the optimization tasks rather the problem definition in comparison with the soft OR approach.

### Facilitated Modeling

Facilitated Modeling is the process by which models are jointly developed between a facilitator and a group, face-to-face, with or without the support of computers (FRANCO; MONTIBELLER, 2010). Facilitated modeling is not a PSM however all PSMs are developed within the facilitation paradigm (FRANCO; MONTIBELLER, 2010).

The design, elaboration and testing of models in group is a relevant tool to engage stakeholders and to provide a more effective results (BALA et al.; ROBINSON et al., 2014; RAMANATH; GILBERT, 2004). There is a number of group-modeling methods, and the facilitated modeling framework can be used in the development of simulation models including system dynamics and discrete-event simulation (ROBINSON et al., 2014; FRANCO; MONTIBELLER, 2010).

The facilitated modeling framework consists of four stages: conceptual modeling, model coding, experimentation and implementation. The main idea is to involve the stakeholders as much as possible in all the modeling steps, in contrast with the expert mode. Ideally all the modeling process would have to be performed by the stakeholders' group however due to practical limitations (e.g., model coding) the group participation is reduced in some stages (ROBINSON et al., 2014).

### Agent-based Modeling

ABM is a modeling and simulation technique that is based on a collection of agents (autonomous entities) that individually assesses its situation and makes decisions on the basis of a set of rules including interactions with other agents and with

an environment (BONABEAU, 2002; MACAL; NORTH, 2010).

A precise definition of an agent is not available in the literature (MACAL; NORTH, 2010). Wooldridge (2009) defines agents as computer systems with two important characteristics. First, they have autonomous action capability. In other words, they are able to decide by themselves. Second, they are capable of interacting with other agents. An agent also needs to be self-contained and to have a state. The agents are structured typically with attributes and methods inside the agents' boundaries. The attributes can be static (e.g., name) or dynamic (e.g., memory of past iterations). The methods include behaviors and other agents' functions. The interactions are possible with other agents and with the environment (MACAL; NORTH, 2010).

The agent-based model development process (MACAL; NORTH, 2010) begins with the questions and problems that the model will address. The next stages comprise the types of agents and environment definitions followed by the agents' behaviors specification, what includes how the agents relates with themselves and with the environment. Finally, the model is validated.

The Overview, Design concepts and Details (ODD) (GRIMM et al., 2020) protocol can be used for agent-based modeling specification. ODD was designed to make it easier to write and read ABM descriptions and to facilitate model replication, while not being overly technical. It can include equations but is based on written text. The protocol is divided in three categories: - overview: provides and overview of the agent-based model; - design concepts: explains how important design concepts were used for ABM and - details: explains the details of the 'machinery' of the model.

The TRACE (TRANSPARENT and Comprehensive Ecological modeling documentation) is a process for comprehensive modeling documentation (GRIMM et al., 2014) and of 'tracing' model development and testing by going backward over the evidence step by step. The main function of the TRACE framework is to provide a modeling

notebook and also a standardized structure and terminology for documentation

### Multimethodology

Multimethodology is a mix of tools, techniques, methods, methodologies and/or paradigms (HOWICK; ACKERMANN, 2011). The literature brings other terms related to this concept such as Methodological Pluralism and Mixed Methods (MIDGLEY, 2015; JOHNSON; ONWUEGBUZIE, 2004).

The development of multimethodologies have several advantages such as the combination of quantitative and qualitative research strengths, stronger evidence for a conclusion through convergence of findings, more confidence in the results, exploration of insights that might be missing when a single method is used and more suitability for the real-world situations. Multimethodology would be possible even when mixing apparently opposing paradigms and it can find in pragmatism the justification to its utilization according to the research questions (MINGERS; BROCKLESBY, 1997; JOHNSON; ONWUEGBUZIE, 2004; VIDAL, 2006). However, the mixing of different methodologies is not free from challenges that can include philosophical, cultural and psychological aspects (MIDGLEY et al., 2016).

The simultaneity and dependence of the methods is an important aspect of the multimethodology definition. Pollack (2009) describes two types of mixed methods designs:

- Serial: soft OR methods are used prior to hard OR methods or vice-versa according to the problem. Shorten and Smith (2017) proposes the terms Explanatory sequential and Exploratory sequential according to the quantitative and qualitative methods sequence;
- Parallel: use of hard and soft OR methods simultaneously. Shorten and Smith (2017) brings the nested category where there is a main and an embedded method used for answering a complementary question.

### PROPOSED MULTIMETHODOLOGY MODEL

The aircraft maintenance is a complex system and the use of modeling and simulation is often required for decision support. However, the involvement of multiple actors with multiple interests and relevant uncertainties, since the CBM is a relatively new paradigm for the aircraft operation, requires the correct characterization of the problem prior to the modeling development.

The process starts with the project planning for addressing the business need or demand. This stage is required for the simulation project structuring, for example the definition of who will be responsible by the OR intervention and for solving the problem situation of interest (FRANCO; MONTIBELLER, 2010). The sponsor, project manager, facilitator and modeling team definitions are one of the activities that are performed in this stage. Other structures can be utilized such as a program or a portfolio (INSTITUTE, 2017).

The next three stages refer to the problem structuring activities. As described in the previous sections PSMs improve the understanding and the modeling of messy problematic situations, what can improve the correct representation of the problem, the systems boundaries, and the objectives of the agent-based model. The 'transitional objects' (MIDGLEY et al., 2013) enhance the stakeholders' engagement and provide focus for dialogue.

The PSM stages are performed before the agent-based model development similarly to the multimethodology architecture of Lehaney and Hlupic (1995) and Tako and Kotiadis (2015), that used the soft paradigm for an improved model definition. This is distinct from the Novani and Mayangsari (2017) approach that uses the agent models as a tool to improve the PSM.

Differently from Tako et al. (2010) or Eden (1994) that used DES and SD respectively, here an agent-based model will be developed. Due to a more intuitive mapping to real social actors than other modeling approaches which are dominated by

Table 1 - Outputs to ABM according to the selected PSM (Source: authors' own elaboration)

PSM	PSM Outputs for ABM
SSM	SSM conceptual model
SODA	Aggregated SODA map
SCA	SCA modeling and design mode
Drama Theory	Scenes resolution
VFT	Strategic, fundamental and mean objectives

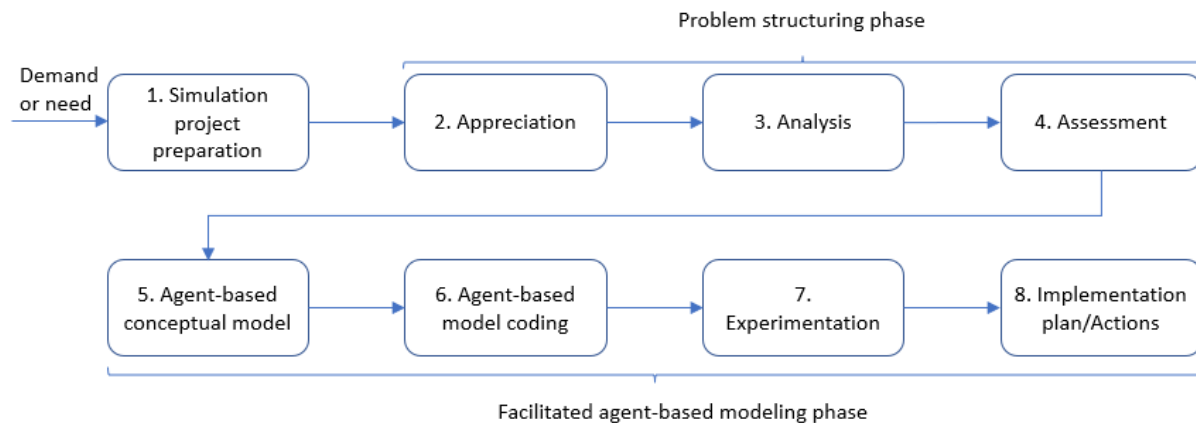


Figure 1–Proposed multimethodology model(Source: authors' own elaboration)

mathematical expressions, especially for those stakeholders that are less formally educated, this simulation approach enhance preliminary model proposal and validation during the first problem structuring stages (appreciation, analysis and assessment), for example regarding the agents, how they behave, what are the relevant rules and the environment restrictions. That can also provide more stakeholders engagement and understanding of the simulation model.

The action stage described by Mingers and Brocklesby (1997) is not performed after the assessment stage since the next step is already defined as the agent-based model development. The different PSMs actions definition techniques, such as the feasibility and desirability analysis (SSM) or the commitment framework (SCA), can be used after the model is developed and implementation actions need to be performed.

Table 1 shows the outputs that can be provided to the ABM process depending on the type of PSM that is used in the proposed model. The PSM provides the following outputs for the ABM process:

- Problem structuring: as the PSMs definition states, one output is a clearer and more structured view of the problem
- Model purpose, scope, goals and entities: by structuring the problem, there is a clearer view of the parts of the problem that a simulation model can address, such as the functions of the SSM relevant systems that can be supported by the ABM. One important output from the PSM to the ABM is an initial view of the entities (agents) and behaviors relevant to the problem.
- Model boundaries and scope: the PSMs execution provides the boundaries for the model, e.g., the regions of the relevant systems where a



Table 2 - Summary of the activities performed in the proposed model (Source: authors' own elaboration)

Stage	Activities	Input	Output
ABM project preparation	<ul style="list-style-type: none"> <li>- Project plan definition</li> <li>- Project team definition (e.g., facilitator, modeling team)</li> <li>- PSM method selection</li> </ul>	<ul style="list-style-type: none"> <li>- CBM decision support problematic situation</li> </ul>	<ul style="list-style-type: none"> <li>- ABM project plan</li> <li>- Resources allocated to the project</li> </ul>
Appreciation	<ul style="list-style-type: none"> <li>- Observation</li> <li>- Interviews</li> <li>- Meetings and workshops</li> <li>- ABM project update (e.g., stakeholders list)</li> </ul>	<ul style="list-style-type: none"> <li>- Project plan</li> </ul>	<ul style="list-style-type: none"> <li>- Problematic situation expressed</li> <li>- Updated ABM project plan</li> </ul>
Analysis	<ul style="list-style-type: none"> <li>- Problematic situation models elaboration</li> <li>- Decision support areas identification</li> </ul>	<ul style="list-style-type: none"> <li>- Collected data from appreciation</li> <li>- Problematic situation representations</li> <li>- Project plan</li> </ul>	<ul style="list-style-type: none"> <li>- Problematic situation models (e.g., SSM conceptual models, SODA maps)</li> <li>- Updates to project plan</li> </ul>
Assessment	<ul style="list-style-type: none"> <li>- Comparison of the PSM models with reality</li> <li>- Adjustments to the problem conceptual models</li> <li>- Decision support areas that the agent-based model should address</li> <li>- TRACE element 1</li> </ul>	<ul style="list-style-type: none"> <li>- Problematic situation models</li> <li>- Project plan</li> </ul>	<ul style="list-style-type: none"> <li>- Model scope, boundaries, purpose and entities</li> <li>- Project plan updates</li> </ul>
Agent-based conceptual model	<ul style="list-style-type: none"> <li>- Agent-based model specification through ODD and facilitated modeling workshops</li> <li>- TRACE element 1 update</li> <li>- TRACE elements 2 to 4 fill</li> </ul>	<ul style="list-style-type: none"> <li>- PSMs models</li> <li>- Expected agent-based model goals, scope, boundaries and entities</li> <li>- Project plan</li> </ul>	<ul style="list-style-type: none"> <li>- Agent-based conceptual model specification</li> <li>- Project plan updates</li> </ul>
Agent-based model coding	<ul style="list-style-type: none"> <li>- Agent-based model coding</li> <li>- Facilitated workshops if necessary</li> <li>- TRACE element 5 fill</li> </ul>	<ul style="list-style-type: none"> <li>- Agent-based model specification</li> <li>- Project plan</li> </ul>	<ul style="list-style-type: none"> <li>- Codified agent-based model</li> <li>- Model documentation</li> <li>- Project plan updates</li> </ul>
Experimentation	<ul style="list-style-type: none"> <li>- Facilitated experiments specification</li> <li>- Facilitated results evaluation and model validation &amp; verification</li> <li>- Model adjustments</li> <li>- TRACE elements 6 to 8 fill</li> </ul>	<ul style="list-style-type: none"> <li>- Codified agent-based model with documentation</li> <li>- Project plan</li> </ul>	<ul style="list-style-type: none"> <li>- Validated &amp; verified model</li> <li>- Experiments results</li> <li>- Project plan updates</li> </ul>
Implementation	<ul style="list-style-type: none"> <li>- Definition, evaluation and prioritization of the actions required for the model implementation</li> <li>- Implementation execution</li> </ul>	<ul style="list-style-type: none"> <li>- Validated &amp; verified agent-based model</li> <li>- PSM and ABM documentation</li> <li>- Project plan</li> </ul>	<ul style="list-style-type: none"> <li>- Implemented agent-based model</li> <li>- Project documentation</li> <li>- Project closing</li> </ul>

simulation model can be applied in the SSM case or the cognitive map constructs where an agent-based model can be developed for

After the problem situation is structured and the proper simulation goals and boundaries are defined, the ABM starts with the agent conceptual model definition and the posterior coding, experimentation, and implementation. The facilitated ABM is required to ensure the model is suited for the stakeholders' needs

(FRANCO; MONTIBELLER, 2010; ROBINSON et al., 2014). This means that the stakeholders are involved in each ABM stage for activities such as model specification, model validation & verification and experimentation design. The more intuitive nature of ABM enhances the stakeholders' participation and feedback.

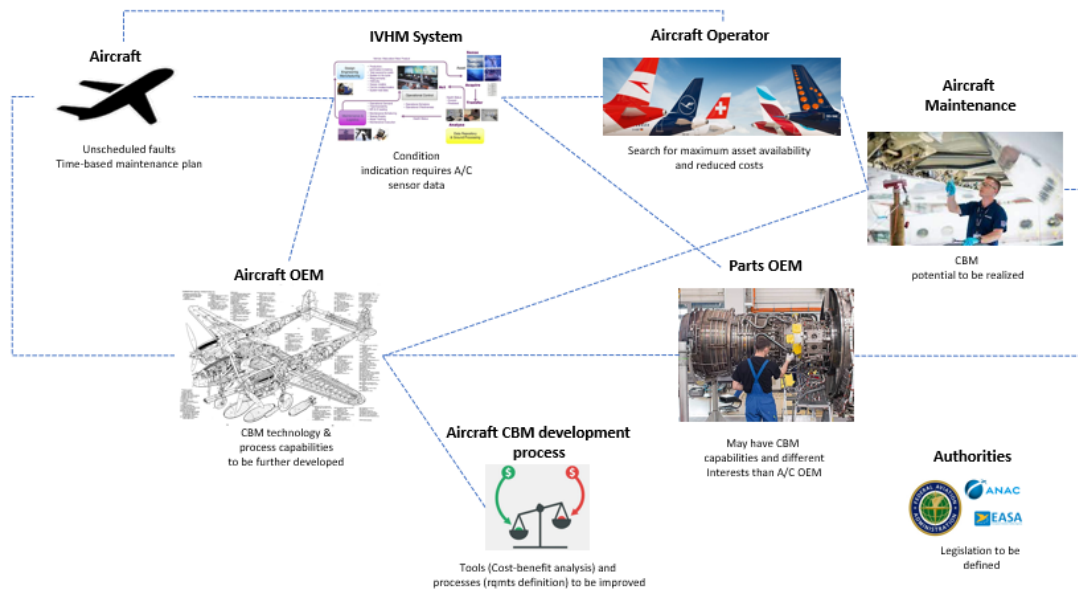


Figure 2 - Problematic situation expressed (Source: authors' own elaboration)

## RESULTS

The problematic situation that is going to be explored is the one related to Condition-based Maintenance (CBM) in the aviation sector. More specifically, the agent-based model development will be performed for decision support to a CBM research and development project. The project team needs to define what is the problem that the CBM project will address and how the simulation will contribute for the project decision support.

### Project Preparation

The ABM work package is part of a bigger research project that will investigate CBM technologies. This is relevant because the ABM project schedule, scope, stakeholders and sponsors are already defined in the CBM research project plan.

The structuring of this CBM project, where the ABM project is located, consisted of workshops with several stakeholders.

After the larger CBM project was structured, the ABM work package was detailed in one meeting with stakeholders more related to this package. The defined time span for the simulation project was three months.

The remaining definitions for this phase are the modeling team, facilitator and ABM project manager and also the selection of the PSM method that is going to be used.

Due to budget constraints and lack of expert knowledge of the PSM and ABM tools, the modeler and the facilitator will be the same person. That is not the ideal configuration, however it is the feasible arrangement for this project. The simulation project manager is the same person responsible for the entire project.

The selection of the SSM was due to the more intuitive characteristics of the rich picture (VOINOV et al., 2018) in the appreciation phase and the strong emphasis in the Analysis and Assessment phase (MINGERS; BROCKLESBY, 1997), that are important for defining the system of interest goals and boundaries.

Table 3 - CATWOE for the selected transformation(Source: authors' own elaboration)

<b>C</b>	Customer	Aircraft operators, aircraft support organization
<b>A</b>	Actors	Engineering departments, information technology, aircraft support, market monitoring, parts manufacturers, certification authorities
<b>T</b>	Transformation	CBM not developed CBM developed
<b>W</b>	World View	Reduce aircraft operation costs and increase aircraft availability
<b>O</b>	Owner	Maintenance Engineering
<b>E</b>	Environment	Legislation, agreements, aircraft development process

### Appreciation

As described in Section 3 this phase comprehends the data collection for the problematic situation.

Interviews were performed so far with maintenance, health monitoring and reliability specialists. Additional stakeholders were identified during the initial interviews and were added during the process. The modeler found in the literature three agent-based models used for CBM (LEE; MITICI, 2020; FENG et al., 2012; SAHNOUN et al., 2019). These models were used for a deeper understanding of the problematic situation and also for asking further questions to the specialists.

Rich pictures were elaborated by the facilitator and iteratively modified by the specialists. Figure 2 shows one of the rich pictures that were used to express the problematic situation.

### Analysis

After the problematic situation was expressed through a rich picture, the transformations that would be required for a vehicle condition-based maintenance were identified. These transformations include:

- CBM development process
- Development of maintenance plans for CBM

- Development of CBM agreements with between the aviation ecosystem players (e.g., aircraft and parts manufacturers)
- Development of operation optimization tools
- Development of CBM data infrastructure (e.g., shared databases)
- Definition of CBM related legislation

From this set of transformation, the first one was chosen since it would be more related to the research project under execution. This transformation was further detailed through the CATWOE framework as summarized in Table 3:

The input for the transformation described in Table 3 is the aircraft condition-based maintenance not developed and the output is the developed CBM for that aircraft type.

With this information it was possible to describe the root definition for this relevant system as: "A system which allows the development of aircraft CBM for operation costs reduction and increased availability that benefits the aircraft operators and the operation support organizations. This system is owned by the maintenance engineering and driven by this area together with a multidisciplinary team that includes the different engineering teams, information technology and aircraft support. The system operates within an environment of aircraft design and operation

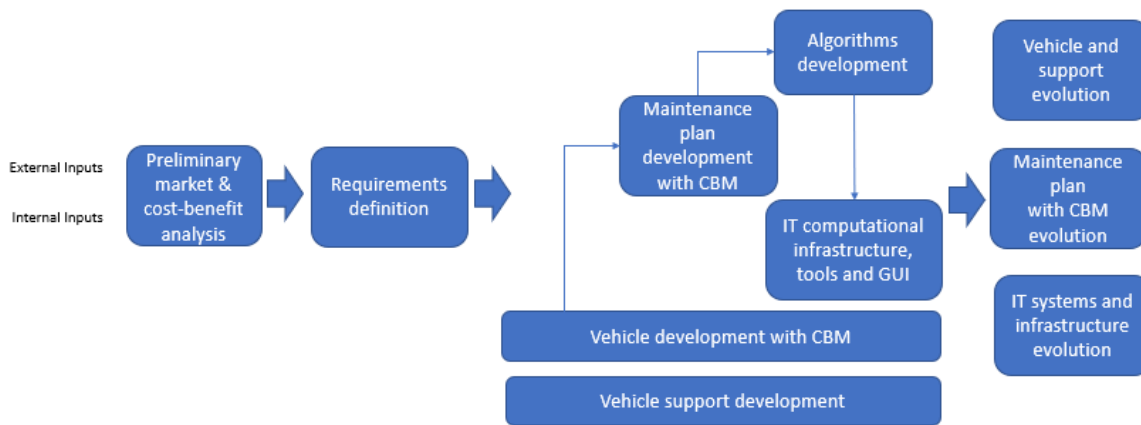


Figure 3–General aircraft CBM development conceptual model(Source: authors’ own elaboration)

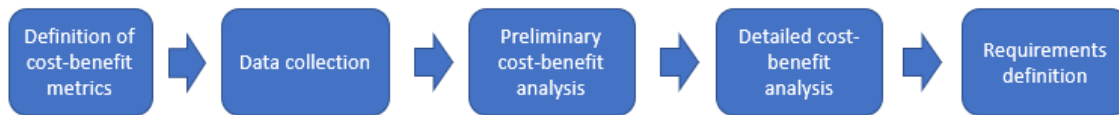


Figure 4 - More detailed view of a CBM development initial tasks(Source: authors’ own elaboration)

legislation, established agreements and development processes.”

The next activity in the Analysis stage was to elaborate the relevant system conceptual model considering different perspectives and points of view. Figure 3 shows an overview of a general conceptual model for a vehicle CBM development.

More details were provided to the preliminary cost-benefit analysis since this is one of the first tasks of a CBM project. Figure 4 shows an overview of a more detailed conceptual model representing the early stages of a general CBM development.

**Assessment**

The assessment phase compares the conceptual models with reality. From the conceptual models shown in the previous section, there are activities that need to be developed and are not related to the decision support provided by a simulation

tool, such as the maintenance plan for CBM. The activity that was identified by the stakeholders that has opportunities for improvement and where the agent-based model tool could be developed is the detailed cost-benefit analysis.

This definition provided the model scope, boundary and purpose, that is to provide support for the detailed cost-benefit analysis and to support the requirements definition. Also, entities (and their behavior) identified in the problem structuring (such as maintenance staff, assets) were also initially defined as relevant to the model.

The TRACE element 1 started to be documented with the problem structuration performed up to this stage. The element 1 description elaborated with the information gathered so far is “the adoption of CBM for some critical components requires a more detailed analysis before the vehicle development starts. This analysis comprehends comparisons with the traditional maintenance approach and the costs (e.g.,

sensors, recorders) that would be required for achieving the expected benefits. The model will be used to assess the potential benefits of the CBM approach for certain components including a reduction in unscheduled and scheduled events and a reduction in the components wasted useful life. The inputs will be based in field data when applicable and the outputs related to the traditional maintenance approach will be compared to existing data. The CBM outputs will be evaluated through experts' critical analysis".

The use case is currently under execution and the agent-based model specification stage is now being performed in a facilitated way, with the stakeholder's participation.

## CONCLUSIONS

This work presented a multimethodology model that integrates problem structuring methods and agent-based modeling. The proposed model is composed of eight stages, one for the project structuring, the next three, based on generic PSM stages, for problem structuring and definition of the agent-based model goal and scope and the last four stages dedicated to facilitated ABM. The modeling process and the model specification are performed and documented through practices available in the literature (TRACE and ODD).

The CBM research project use case shown that the problem structuring provided a holistic view of the problem. The PSM models were useful for the stakeholders to exchange knowledge and to think in the problematic situation in a more tangible way. The PSM also provided a structured process for the agent-based model goal, scope and entities definition. There are also some drawbacks that were observed, such as the lack of knowledge in the PSMs, what often produced questions regarding the goals of the process stages, and the apparent distance from the problem structuring and the agent-based model building. However, the advantages are much greater than the drawbacks in our opinion and the agent-based model building have a

stronger foundation due to a more robust problem structuration.

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