Model-Based System Engineering Adoption for Trade-Off Analysis of Civil Helicopter Fuel Supply System Solutions

Liu Weihao, Guo Yuqiang, Chen Qipeng, and Zhao Hui

1 Introduction

For complex system development,it is required that the requirements management, architecture development and production teams should effectively collaborate to provide timely, useful, and cost-effective products. Traditional Document-Based System Engineering (DBSE) method stores and transfers project information in documents, which is labor-intensive and needs plenty of manual analysis, review and inspection. MBSE is the formalized application of modeling to support system requirements, design, analysis, optimization, verification and validation [1, 2]. By using system modeling tools, an integrated, consistent and clear system model can be generated to give a unified representation, allowing for good understanding of the relationships between stakeholders, organizations and their impacts. Moreover, the system model provides the opportunity to link various domain-specific tools together to produce a model-based framework for a systems engineering project, and more complex verification and validation of the system can be conducted before a real system is produced.

In recent years, exploratory work on how to use MBSE method to realize integrated product design, simulation, optimization and verification in the digital virtualization environment has been carried out by many famous enterprises worldwide including NASA, Boeing and Airbus. It has been demonstrated that using MBSE method can significantly reduce the R&D risks and cost, shorten the R&D time [3–6].

Fuel Supply System is a crucial complex system involving mechanical, electrical and hydraulic technologies. According to CCAR 29 regulations, one of the main

L. Weihao (✉) · G. Yuqiang · C. Qipeng · Z. Hui
China Helicopter Research and Development Institute, Route Dongsan, Airport Economic Zone, Tianjin 300308, China
e-mail: Liuwh001@avic.com

G. Yuqiang
e-mail: Guoyq001@avic.com

311

functions of Fuel Supply System is to provide the Engine with sufficient fuel required under all operating and maneuvering conditions [7].

The present work is a practice to use a MBSE method for the development of helicopter Fuel Supply System. A system model is first architected with a practical modeling methodology and an efficient modeling tool based on the standard SysML. Then the model is used to make a trade-off analysis to choose an optimal solution architecture before subsequent detail design and manufacture begins.

2   Problem Description

According to the Engine Manual of Mi-26 helicopter, the pressure range at the Engine fuel inlet is so narrow that Fuel Supply System architecture design and booster pump selection will be complex (Fig. 1).

Generally, a simple and common civil helicopter Fuel Supply System model is presented in Fig. 2 considering the basic requirements from CCAR 29.951 & 953 & 955. Pressurized fuel is supplied to the engine by booster pump located in feeder tanks. There are also Non-Return Valve, Pessure transducer and SOV.

The challenge for Fuel Supply System design are from following requirements:

- According to the stakeholder's requirements, the height between the booster pump outlet and the Engine fuel inlet is 3.88 m, and the G-Load requirements is −0.5 to +3.5 g. In the fuel pipeline the pressure variation will reach up to 118.6 kPa due to G-Load only.
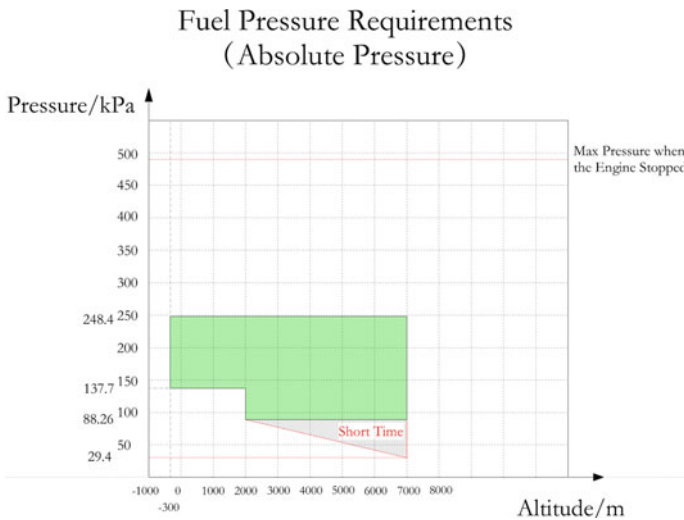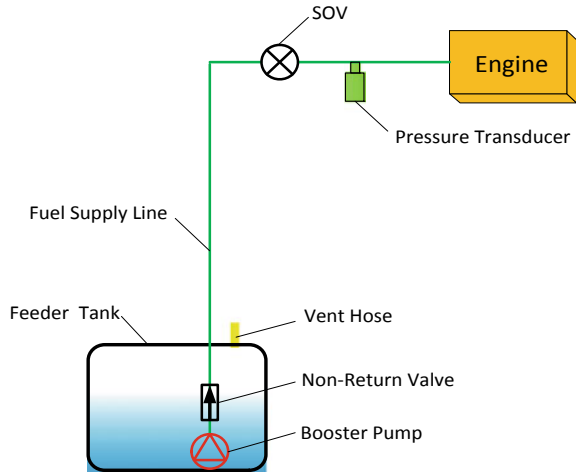

Fig. 1   Required fuel pressure (absolute pressure) by the Engine at different altitudes

Fig. 2 Fuel supply system general architecture

- Existing commercial off-the-shelf booster pumps possess a pressure variation of approximately 30 kPa due to engine consumption.
- Flow resistance due to various temperature, fuel type and velocity etc.

Thus, the total pressure variation will reach up to 148 kPa, which exceeds the Engine fuel pressure limitations, as shown in Fig. 3.

According to the Fuel Supply System architecture (Fig. 4), the fuel pressure at the Engine fuel inlet can be computed as followings:

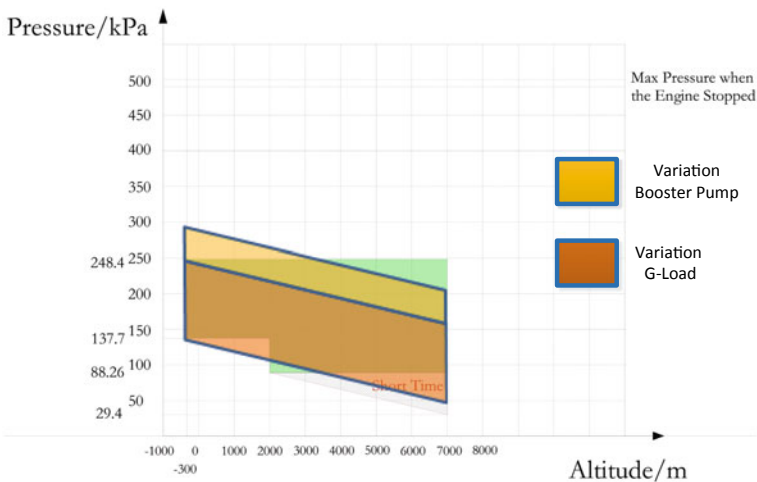1. H_1 is the plumb height between fuel surface and booster pump inlet.

Fig. 3 Comparison of the required fuel pressure by the Engine with its variations caused by G-Load and booster pump characteristics

Fig. 4 General fuel supply
system schematic diagram

2. H_2 is the plumb height between Engine inlet and pump outlet.
3. P_a is ambient pressure associated with altitude h and relevant ambient
    temperature T. It will be referenced as $P_{a(h,T)}$.
4. ΔP_{g1} is the pressure of fuel height H_1. It is affected by G-Load factor δ, fuel
    density ρ and height H_1. It will be referenced as $\Delta P_{g1(\delta,\rho,H_1)}$.
5. ΔP_p is the booster pump pressure associated with pipeline fuel flow rate Q and
    fuel temperature T_f. It will be referenced as $\Delta P_{p(Q,T_f)}$.
6. ΔP_{g2} is the pressure variation mainly caused by the G-Load of helicopter. It is
    affected by G-Load factor δ, fuel density ρ, and height H_2, therefore will be
    referenced as $\Delta P_{g2(\delta,\rho,H_2)}$.
7. ΔP_f is the fuel pressure loss due to pipeline friction. It's a function of pipeline
    diameter ϕ, height H_2, flow rate Q, fuel density ρ and fuel temperature T_f,
    therefore will be referenced as $\Delta P_{f(\phi,H_2,Q,\rho,T_f)}$.
8. P_E is the Engine inlet fuel pressure. The limitation of P_E is effected by altitude
    h according to Engine manual, therefore the permitted engine inlet pressure will
    be referenced as $P_{E(h)}$.

Then, P_E can be expressed by the equation below:

$$P_E = P_{a(h,T)} + \Delta P_{g1(\delta,\rho,H_1)} + \Delta P_{p(Q,T_f)} - \Delta P_{g2(\delta,\rho,H_2)} - \Delta P_{f(\phi,H_2,Q,\rho,T_f)} \quad (1)$$

where:

$$\Delta P_{g1(\delta,\rho,H_1)} = \delta\rho g H_1 \quad (2)$$

$$\Delta P_{g2(\delta,\rho,H_2)} = \delta\rho g H_2 \quad (3)$$

Usually, T is approximately equal to fuel temperature T_f. Thus, from Eq. (1),

$$P_E - P_{a(h,T_f)} = \Delta P_{p(Q,T_f)} - \delta\rho g(H_2 - H_1) - \Delta P_{f(\phi,H_2,Q,\rho,T_f)} \quad (4)$$

Considering $P_{E(h)}$, following inequality should be satisfied:

$$\left| P_{E(h)} - P_{a(h,T_f)} \right| \geq \left| \Delta P_{p(Q,T_f)} - \delta \rho g (H_2 - H_1) - \Delta P_{f(\phi,H_2,Q,\rho,T_f)} \right| \quad (5)$$

Also δ has to be kept in accordance with the G-Load of the helicopter. Considering the extreme values of δ, following inequality should be satisfied:

$$\begin{cases} P_{E(h),max} - P_{a(h,T_f)} \geq \Delta P_{p(Q,T_f)} - \delta_{min} \rho g (H_2 - H_1) - \Delta P_{f(\phi,H_2,Q,\rho,T_f)} \\ P_{E(h),min} - P_{a(h,T_f)} \leq \Delta P_{p(Q,T_f)} - \delta_{max} \rho g (H_2 - H_1) - \Delta P_{f(\phi,H_2,Q,\rho,T_f)} \end{cases} \quad (6)$$

According to Eq. (6), $\Delta P_{p(Q,T_f)}$ and $\Delta P_{f(\phi,H_2,Q,\rho,T_f)}$ mainly depend on the inherent characteristics of booster pump, fuel supply hoses and fuel type. Thus, the relative pressure at the Engine fuel inlet $P_{E(h)} - P_{a(h,T_f)}$ will be impacted significantly by height $H_2 - H_1$.

According to Eq. (6), one possible solution is to reduce the height $H_2 - H_1$, which means the fuel supply line should be shorten by putting the feeder tank on the upper deck of the helicopter (Fig. 5). The feeder tank will be supplied by the Fuel Transfer System from the Auxiliary Tank. Float switch and actuated valve will detect the high fuel level and cut off the fuel supply from the auxiliary tank to the feeder tank in order to prevent overpressure. The feeder tank connects with the outside through vent hoses in order to keep ambient pressure. Fuel stored in the feeder tank is supplied to the Engine with the help of booster pump.

Fig. 5 Alternative fuel supply system architecture
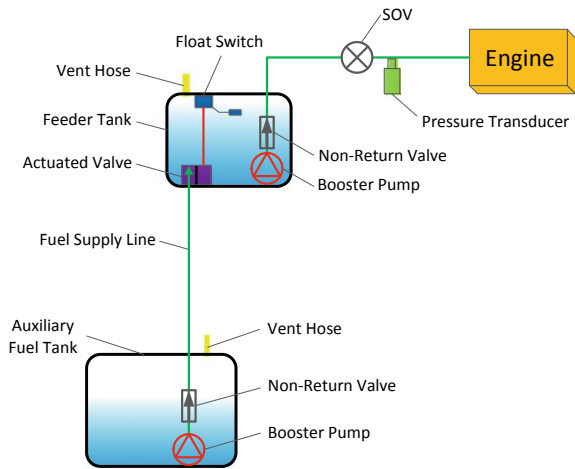
3 System Architecture

Since the system model is the basis of MBSE activities, it is of significance to architect system with appropriate modeling language, tool and methodology. In previous work, the system architecture is based on the Object Management Group's (OMG) Systems Modeling Language (SysML) and produced by a commercial modeling tool Magic-Draw with a practical modeling methodology MagicGrid. As the present work is dedicated to trade-off analysis of system solution architectures, only the problem and the solution domains of MagicGrid methodology are adopted. The remaining sections in this chapter will present model artifacts produced in the modeling workflow.

3.1 Problem Domain

The purpose of the problem domain is to analyze stakeholder needs and refine them with SysML model elements to get a clear and coherent description of what problems the system of interest (SoI) must solve. From the black-box perspective, it focuses on how the SoI interacts with the environment without getting any knowledge about its internal structure and behavior.

Stakeholder needs of the helicopter Fuel Supply System are captured by a requirement table shown in Fig. 6. It includes airworthiness regulations, functional and performance requirements, which are derived from the Fuel Supply System's superior system, i.e. the fuel system. Non-functional stakeholder needs serve as high-level

| #	Name	Text
1	⊟ ⓡ SN-1 CCAR-29.955	The fuel system for each engine must provide the engine with at least 100% percent of the fuel required under all operation and maneuvering conditions to be approved for the rotorcraft.
2	ⓡ SN-1.1 Fuel pressure	The fuel pressure corrected for accelerations (load factors), must be within the limits specified by the engine type certificate data sheet.
3	ⓡ SN-1.2 Fuel level	The fuel level in the tank may not exceed that established as the unusable fuel supply for that tank under ccar 29.959, plus that necessary to conduct the test.
4	ⓡ SN-1.3 Fuel head	The fuel head between the tank and the engine must be critical with respect to rotorcraft flight attitudes.
5	ⓡ SN-1.4 Fuel flow transmitter	The fuel flow transmitter, if installed, and the critical fuel pump (for pump-fed systems) must be installed to produce (by actual or simulated failure) the critical restriction to fuel flow to be expected from component failure.
6	ⓡ SN-1.5 Power resource	Critical values of electrical power or other source of fuel pump motive power must be applied.
7	ⓡ SN-1.6 Fuel property	Critical values of fuel properties which adversely affect fuel flow are applied during demonstrations of fuel flow capability.
8	ⓡ SN-1.7 Fuel Filter	The fuel filter required by CCAR.29.997 is blocked to the degree necessary to simulate the accumulation of fuel contamination required to activate the indicator required by CCAR.29.1305 (a) (17).
9	⊟ ⓡ SN-2 Functional requirements	
10	⊟ ⓡ SN-2.1 Supply Fuel to the Engine.	
11	ⓡ SN-2.1.1 Fuel supply capacity	Supply to the engine with fuel according to the pressure, flow and temperature requirements in all flight envelopes.
12	ⓡ SN-2.1.2 Fuel pressure monitoring	Monitor the fuel pressure supplied to the Engine.
13	ⓡ SN-2.1.3 Pump status monitoring	Monitor the status of the pump.
14	⊟ ⓡ SN-2.2 Shut off fuel supply	
15	ⓡ SN-2.2.1 Fuel shut off capacity	Provide means to cut off the fuel supply to the engine.
16	ⓡ SN-2.2.2 Shut-off valve monitoring	Monitor the status of the shut-off valve.

Fig. 6 Stakeholder needs
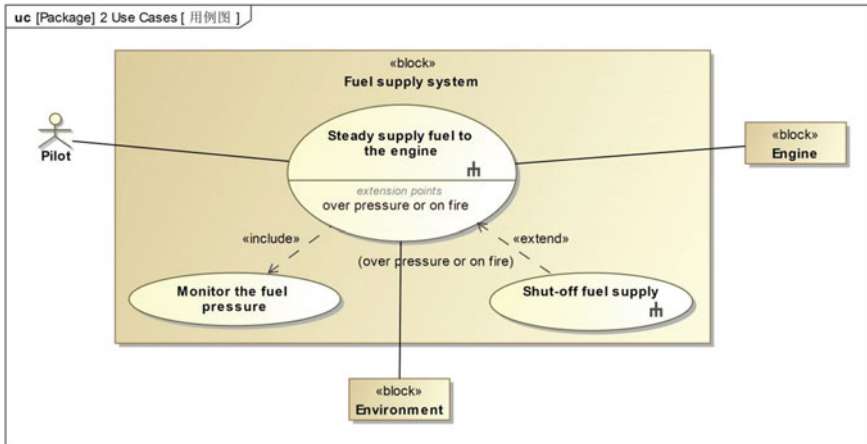
Fig. 7 Use cases

key performance indicators that should be checked within the solution domain model, such as the fuel pressure at the inlet of the engine. The functional stakeholder needs include "fuel supply to the Engine" and "cut off the fuel supply", which are two key functions that the Fuel Supply System must have.

Functional stakeholder needs are refined with use cases and use case scenarios. Three use cases in the system context are captured by a SysML use case diagram, as shown in Fig. 7. They are more precise than the stakeholder needs in telling what the pilots expected from it, what external systems it interacts with, and what they want to achieve by using it.

The primary use case scenario, "Steady supply fuel to the engine", is captured by a SysML activity diagram shown in Fig. 8. It can be found that an activity "Supply fuel to the engine" is allocated to the Fuel supply system by swimlanes. Moreover, the external interaction interfaces between the Fuel Supply System and the external systems can also be identified. Summarizing all use case scenarios, all required activities and external interaction interfaces can be obtained.

Then, the Fuel Supply System can be unfolded from the white-box perspective. The required activities for the Fuel Supply System are further refined with decomposed sub-functions, as shown in Fig. 9. Moreover, the logical subsystems and internal interaction interfaces can also be identified.

3.2 Solution Domain

Once the problem domain analysis is completed and stakeholder needs are transferred into the model, it is time to start thinking about the solutions. Figure 10 shows a system requirements specification described by a SysML requirement diagram. It is
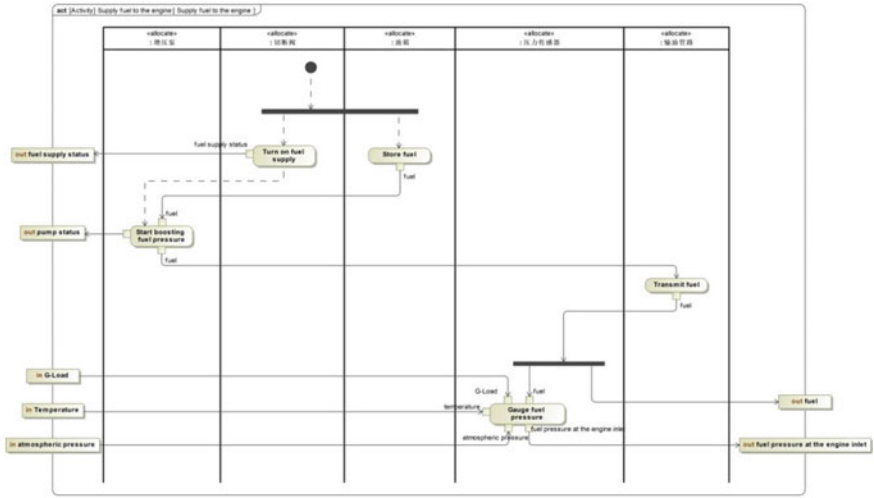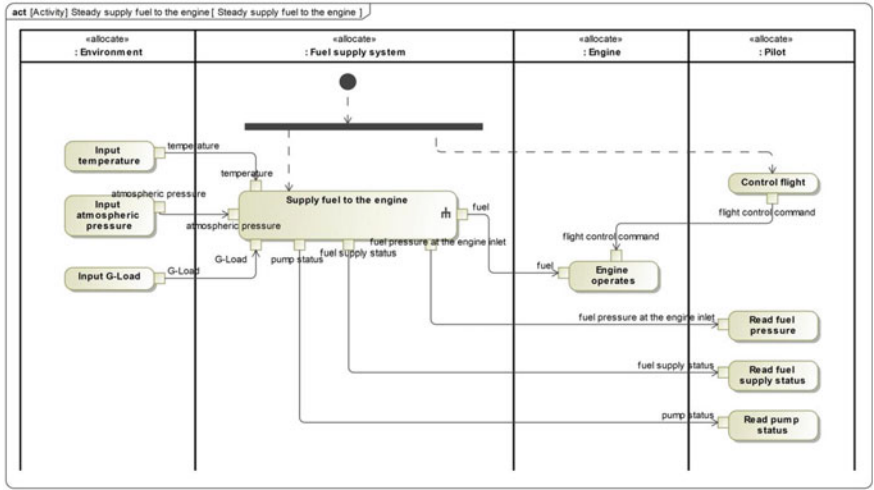
Fig. 8 Primary use case scenario

Fig. 9 Refinement of the primary activity

identified from the problem domain model to refine the activities, parts, interfaces and ports captured in problem domain. Based on it, a high-level solution architecture (HLSA) can be given by a SysML block definition diagram from the problem domain model, as shown in Fig. 11.

According to the HLSA, two detailed solution architectures are considered in present work. In the first one, the feeder tank is placed at the bottom of helicopter (Fig. 2). It has been found that the fuel pressure at the Engine fuel inlet due to plumb
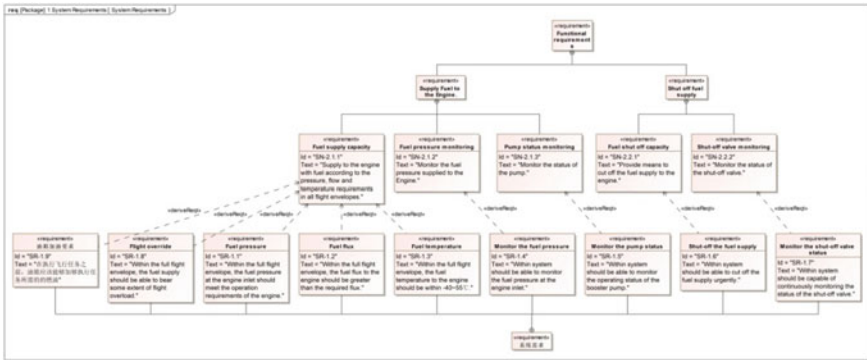
Fig. 10 System requirements specification
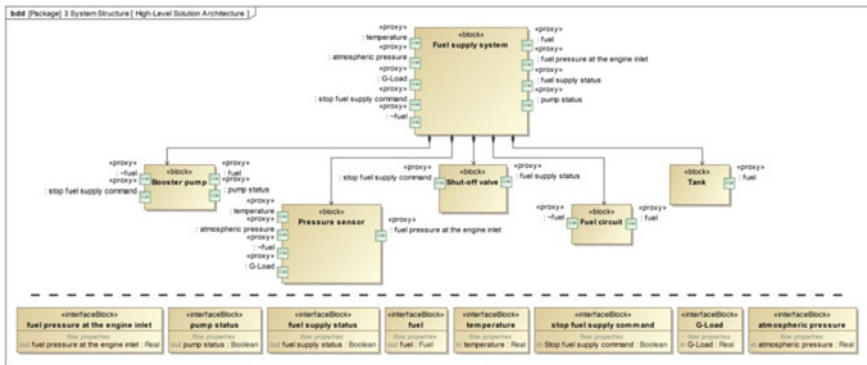
Fig. 11 High-level solution architecture

height of fuel supply line and G-Load will vary wildly. An alternative architecture puts the feeder tank at the height close to the Engine (Fig. 5). The calculation model for the former is described by a SysML parametric diagram shown in Fig. 12. With the altitude (A), fuel temperature (T), G-Load factor (G-Load), and fuel pressure at the outlet of the booster pump (Pp) as the input, the fuel pressure at Engine fuel inlet (Pe) can be immediately evaluated and verified against the required range of the Engine.

4 Trade-Off Analysis

Once detailed solution architectures are determined, a trade-off analysis can be performed to choose the optimal one. Moreover, the selection of existing commercial off-the-shelf booster pumps is also considered in this analysis. Table 1 gives six
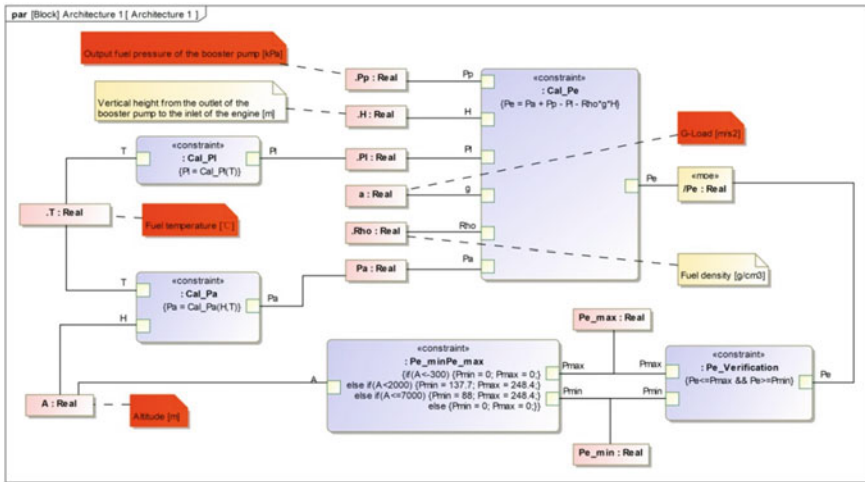
Fig. 12 Calculation model for the fuel pressure at the engine inlet in solution architecture 1

Table 1 Six practical solutions considered in present trade-off analysis

	Pump RLB-40	Pump RLB-48	Pump RLB-111
Architecture 1	(a)	(c)	(e)
Architecture 2	(b)	(d)	(f)

practical solutions from two solution architectures and three booster pumps.

A trade-off procedure is concluded in Fig. 13. For a specific flight mission, the altitude (A), fuel temperature (T), G-Load factor (G-Load), and fuel pressure at the outlet of the pump (Pp) vary within certain ranges. They are first discretized and combined into different operating points. Those operating points are inputted into the calculation model represented by the SysML parametric diagram, which integrates Matlab/Simulink models to calculate and verify the fuel pressure at the Engine fuel inlet (MoE). Only when all operating points pass the verification can a solution be asserted as feasible and safe for the flight mission. In present SysML modeling tool (No Magic MagicDraw), the failed operating points will be marked red in the right sidebar. It is obvious that only the solution (f), i.e. architecture 1 combined with pump RLB 111, passes the verification, while the other five solutions are failed.

In order to give a deeper analysis, the results are displayed graphically in Fig. 14. The outer frame represents the allowable pressure range at the Engine fuel inlet. The cubes distinguished with different color represent the actual pressure that supplied to the Engine. If the any part of the cubes exceeds the boundary of the outer frame, it means that the operating point relevant to the "part" cannot meet the pressure requirement of the Engine. Obviously, conclusions can be drawn as follows:
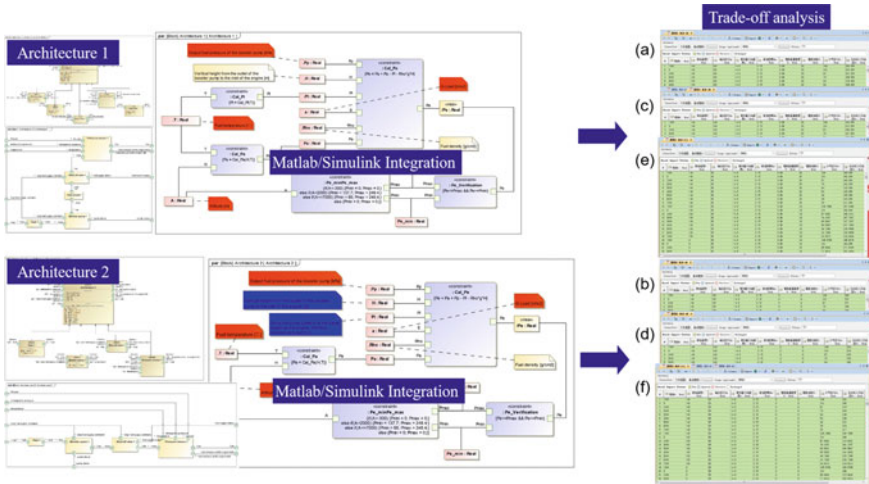
Fig. 13 Trade-off procedure

1. Among the 6 solutions, only the solution (f) "Architecture 2 + Pump RLB-111" passes the verification. It's found that architecture 2 can effectively reduce the pressure variation and still shows potentiality for better pump selections.

2. The fuel pressure variation at the Engine fuel inlet obtained by architecture 2 is significantly smaller than architecture 1 considering the same pump and same operating point. In architecture 1, the pressure is more sensitive to the G-Load factor because the plumb height between the outlet of the booster bump and the inlet of the Engine is much higher.

5   Conclusion

A complete process of developing a Fuel Supply System using MBSE method is presented in this paper, including requirements analysis, function analysis, system architecture definition and trade-off. It provides a capability that MBSE is a proper way to deal with the Fuel Supply System development.
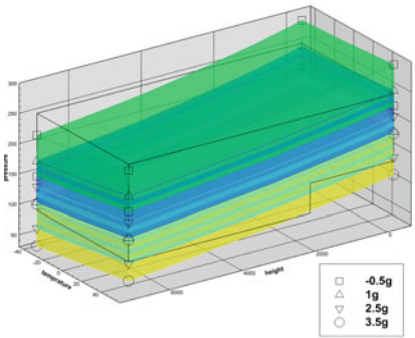
Variable booster pump, which has the ability to adjust the output fuel pressure ($\Delta P_{p(Q,T_f)}$) accordingly, might be another possible solution for this problem. However, more detailed requirements shall be analyzed and more complex joint simulation between system and equipment model need further discussion.
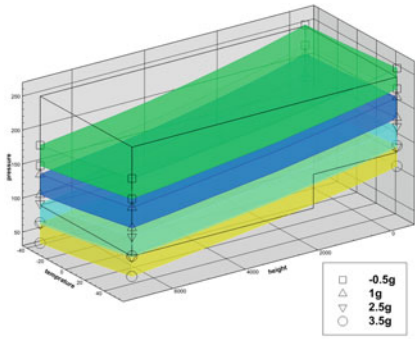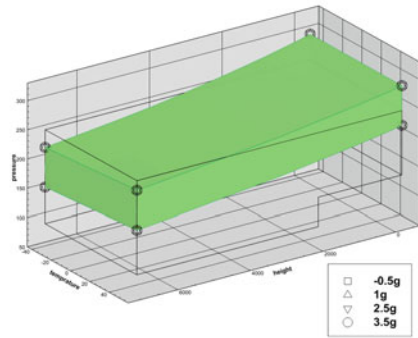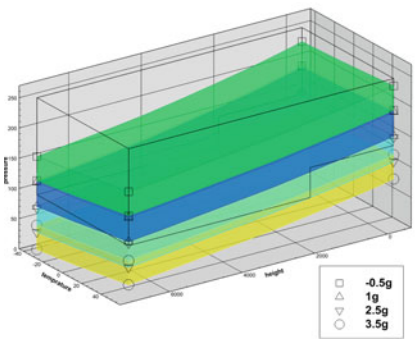
(a) Architecture 1 + Pump RLB-40
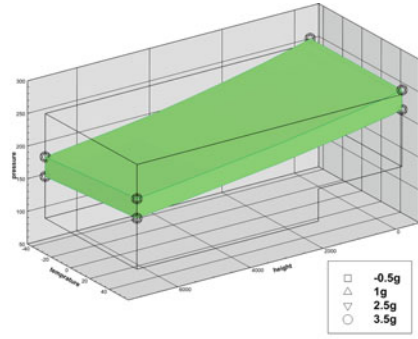
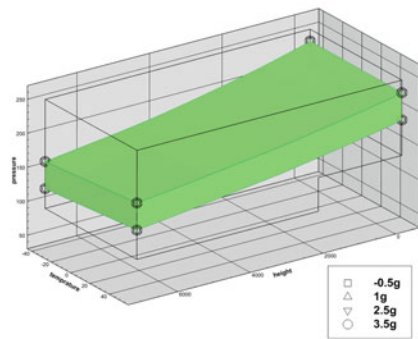(b) Architecture 2 + Pump RLB-40

(c) Architecture 1 + Pump RLB-48

(d) Architecture 2 + Pump RLB-48

(e) Architecture 1 + Pump RLB-111

(f) Architecture 2 + Pump RLB-111

Fig. 14 Results of trade-off analysis for six practical solutions

References

1. INCOSE: INCOSE Systems Engineering Handbook, Version 4.0 (eds.) (2015)
2. ISO/IEC: ISO/IEC 15288: 2008 Systems and software engineering-System lifecycle process (2008)
3. Motamedian, B.: MBSE applicability analysis. Int. J. Sci. Eng. Res. (2013)
4. Arnould, V.: Using model-driven approach for engineering the system engineering system. In: 13th annual conference on system of systems engineering (SoSE) (2018), pp. 608–614
5. Zhang, S.J., Li, Z.Q., Hai, X.H.: Safety critical systems design for civil aircrafts by model based systems engineering (in Chinese) (2018), pp. 299–311
6. Qian, M.: Design method of civil aircraft functional architecture based on MBSE (2019)
7. CCAR- 29-R2 Airworthiness Standards Transport Category Rotorcraft.