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Understanding Low-Cost Satellite Development: The Delfi-PQ Case Study

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The Delft University of Technology has been working on Delfi–PQ, a 3P PocketQube developed by Aerospace Engineering students during their education. The satellite, while being only 50x50x178 mm and having a mass of 545 g, shares the same problems and requirements as larger satellites. Delfi–PQ was launched on January 13th, 2022, and stayed operational till it decayed on January 9th, 2024. This paper presents the design concept, development, and cost of Delfi–PQ to help other teams in their development. This paper will provide a detailed overview of the hardware cost of Delfi–PQ. This cost breakdown will be from multiple angles; system costs, components, structural pieces, and the cost of a specific function in a subsystem. Such a detailed breakdown can be used for future satellite cost modeling and create a foundation for other institutions for their satellite projects.

Key Words: Delfi–PQ, PocketQube, Miniaturized Spacecraft, Cost-Effective, Satellite Cost

1. Introduction

Over the past 20 years, there has been an exponential increase in satellite launches, largely driven by the advent of smaller satellite classes such as Micro, Nano, and Pico satellites. These satellites are often promoted as cost-effective alternatives to larger satellites, which is accurate to a certain extent, however, there is insufficient insight into their development costs. Academic satellite projects frequently use terms like "cost-effective" and "low-cost," but what do these terms actually mean in this context? What factors contribute to making a satellite "low-cost"? It is clear that the definition includes more than just the monetary expenditure on a project, and this paper aims at answering those questions.

PocketQubes (PQs) are a new type of modular, cuboid satellite platform with individual "unit" dimensions of 50x50x50 mm and a mass of 250 g.[1] Like CubeSats, these units are referred to as 1P. Since 2017, Delft University of Technology has been developing a 3P PocketQube with dimensions of 50x50x178 mm, viewing this compact design as a stepping stone toward creating even smaller satellites. The compact size of PQs inherently limits the size of subsystems and payloads, driving a shift in mission concepts to build more complex missions from smaller components. Due to their small size and relatively low development cost, PQs can be launched in large quantities to create a distributed sensor swarm, further lowering overall mission costs. The main objective of Delfi-PQ is to lay the groundwork for a series of PocketQubes developed in Delft.[2,3]

This paper presents the end-to-end development of Delf-PQ, shown in Fig. 1. Firstly, explaining the pocket cube standard, and later, the PQ9 electrical standard for interchangeability of the subsystems. Additionally, the subsystem development approach from a subsystem core to specific functionalities that have been added to the core as a result of creating the bus of the satellite. Detailed block diagrams and the cost of every subsystem are given in respective sections. Lastly, the cost of the Delfi–PQ hardware has been explained during the whole development cycle, the number of revisions, and the cumulative costs throughout the years of development. Delfi-PQ was launched on January 13th 2022, and it was operational until it decayed on January 13th, 2022.

Fig. 1. The Delfi-PQ flight model.

This cost breakdown of the Delfi–PQ project, from its initial concept to its deployment in orbit, aims to guide other institutions interested in developing their own PocketQubes. The aim of this paper is to present a reference point for future PocketQube development planning, focussing on the hardware cost.

2. Delfi-PQ and the PocketQube Concept

The PocketQube concept was first introduced in 2009 by Prof. Robert J. Twiggs, in collaboration with Morehead State University and Kentucky Space.[4,5] These small, cuboid-shaped platforms have dimensions of 50x50x50 mm and an approximate mass of 250 g. The first PocketQubes were successfully launched in 2013 as part of the UniSat5 mission.[4,5]

In 2017, the Space Department at Delft University of Technology shifted its focus towards further miniaturization of space technology, initiating the development of extremely small satellites—almost an order of magnitude smaller than traditional CubeSats. Although PocketQubes and other pico-satellites

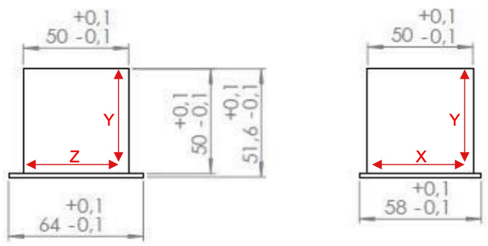

Fig. 2. 1P Mechanical Drawing.

(ranging between 100 g and 1 kg) are still in the early stages of development, they are often viewed primarily as educational tools, similar to how CubeSats were initially perceived. Delft University of Technology aims to challenge this notion by demonstrating the significant potential of PocketQubes beyond education. Their small size drives innovative approaches to space technology development, leading to new possibilities for larger spacecraft and the inclusion of PocketQube-sized components in CubeSat platforms, thereby freeing up space for additional payloads.

These smaller spacecraft could offer significant cost-efficiency benefits, especially when deployed in extensive networks that exceed the scale of existing CubeSat constellations. Delft University of Technology aims to provide a solid framework for future developments in this satellite category and to serve as a reference for those interested in this area.[6]

The team also evaluated different size options and decided to develop a 3P PocketQube, positioned between CubeSats (1U or 0.5U) and PocketQubes. A 3P PocketQube has a volume of 445 cm^3, compared to 1000 cm^3 for a 1U CubeSat and 500 cm^3 for a 0.5U CubeSat. If the team can demonstrate that the performance of a 1U CubeSat can be achieved more quickly and at a lower cost using a PocketQube, it could enable to larger projects involving swarms of these miniaturized satellites.

Additionally, the Delft University of Technology has developed both mechanical and electrical standards for PocketQubes. The mechanical standard, based on the original PocketQube design, was created in collaboration with Alba Orbital and Gauss Srl. to define a universal deployer, which allows for more players to enter the market. The electrical standard, named PQ-9, was developed to include a stacking connector similar to the one used in CubeSats, facilitating interchangeable subsystems and encouraging independent component development as shown in Fig. 3. The idea was inspired by the CubeSat's success, which initially relied on a common connector (PC104) to integrate components from different manufacturers into the same satellite system.

Table 1. PQ external dimensions.

Number of units (P)	External Dimensions w/o backplate (mm)	Sliding backplate dimensions (mm)
1P	50x50x50	58x64x1,6
2P	50x50x114	58x128x1,6
3P	50x50x178	58x192x1,6

3. Delfi–PQ Design

The development cycle for the satellite was carefully planned to accommodate the academic calendar, ensuring active student

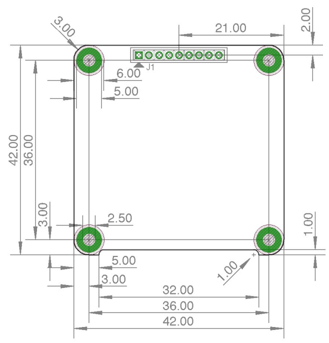

Fig. 3. PQ9 Printed Circuit Board (PCB) dimensions.

participation. Due to the transient nature of student involvement, typically lasting only three to six months, the project was structured into discrete, manageable tasks. This modular approach required clear interface definitions early in the design process to ensure system independence and prevent changes in one system from impacting others. Over three years, the satellite underwent several design iterations, influenced by changing launch requirements and schedules, which ultimately enhanced the design and functionality of the subsystems. Two full design cycles were completed, with some systems updated as many as four times. After assembly, an additional two-year delay in the launch allowed further refinement of the software and ground systems.

The design strategy employed a bottom-up approach, starting with several high-level requirements: the satellite was to weigh under 750 grams to comply with launch adapter specifications, it was to be a 3P PocketQube by team decision, and it featured an unregulated power bus with a maximum of 4.5 W. Each subsystem was designed to regulate its own power and include protective circuitry against single event upsets, ensuring modularity. The mission was designed to use amateur frequencies, compatible with existing ground infrastructure. Development of the subsystems was mostly sequential, leveraging iterative improvements across different systems, with the communication system and structural components developed concurrently with other subsystems. This methodical approach is detailed in the respective development order of the subsystems, as shown in Fig. 4.

All the mentioned subsystems are shown in Fig. 5.

3.1. Defining A Core

A standard core was designed to create a reliable system and reduce the required iterations in return reducing the hardware cost and development time.

According to the PQ-9 standard,[7] a PQ board measures 42x42 mm, as shown in Fig. 3. Despite shrinking system foot-

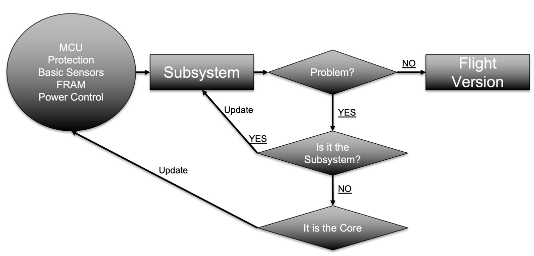

Fig. 4. Subsystem Core Development Cycle.

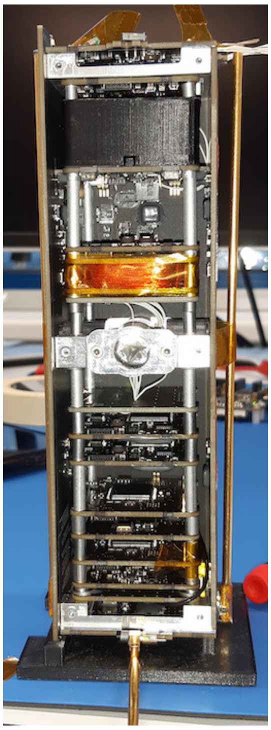

Fig. 5. Delfi-PQ interval view (-X panel removed), subsystem stack (upside down).

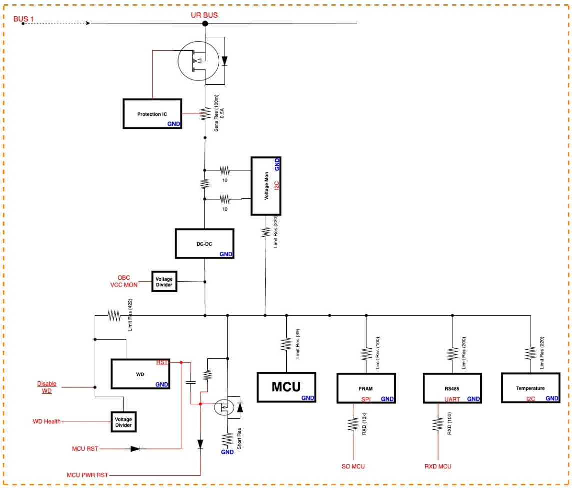

Fig. 6. Delfi-PQ, core electronics block diagram.

prints, the core functionality and components remain aligned with those found in traditional CubeSat systems, which results in a higher density on each board. To ensure modularity, every subsystem is equipped with a Micro-Controller (MCU), a DC-DC converter, and tailored software. We introduced a "core" concept that encapsulates the essential functionality common across all subsystems, detailed in Fig. 4, which illustrates the development and decision-making cycle. This standardized PQ core includes an MCU, a DC-DC converter, circuits for voltage-current monitoring and protection, a temperature sensor, an RS485 transceiver, a watchdog, and persistent parameter memory utilizing Ferroelectric memory (FRAM) that supports random access, persistent storage, and extensive write cycles. With this core in place, updating or adding new subsystems with specialized functions is streamlined to approximately one month, including production and testing phases. The standardized core also forms the foundation for most of the software, which can be largely reused, with only the subsystem-specific functionality requiring development.

The cost of the electronics for this core is approximately 65 Euros. Considering that during the development of the Delfi-PQ, manufactured processes were always in 5 pieces at a time, the core will be 325 Euros and the additional functionalities and PCB costs will be added to the number.

This standardized PQ core also creates a baseline for the required software. Most of the software can be reused as only system-specific functionality needs to be written.

3.1.1. Protection Circuit

The standardized PocketQube core protects against radiation effects common in space. Many satellite projects, including commercial ones, use cost-effective Commercial Off-The-Shelf (COTS) components that aren't radiation-hardened, as radiation-hardened alternatives can be significantly more expensive. To manage single-event latch-ups—sudden increases in power consumption due to high-energy particles—a current-limiting resistor is used to keep components within safe operating limits. In case of latch-up, a circuit breaker temporarily cuts power, allowing the component to reset. If needed, the system can also trigger a full satellite power cycle to restore functionality, an approach that has proven effective in orbit.

3.2. Satellite Bus

Delfi-PQ consists of an electrical power system, battery, solar panels, the communication system as a combination of the main board, power amplifier, and phasing board, a precursor of an LNA for a future miniaturized space telescope, on-board computer, secondary on-board computer as an in-orbit laboratory, antenna deployment board, and attitude determination and control system with a 3–axis magnetotorquers.[8] Details and images of these systems are given in.[9] In this section, high–level design of the subsystems are explained as block diagrams.

- Electrical Power System - EPS

The electrical power system (EPS) consists of three main components: the main board, battery board, and solar panels. In addition to the EPS core (Fig. 6), Fig. 7 shows the inhibit switches and the four unregulated power bus controls. Each bus is equipped with a current-limiting switch; BUS–1, which powers the communication system and On-Board Computer (OBC), is normally ON, while the other buses remain off unless required. The EPS controls these four unregulated buses with a voltage range of 3 V to 4.2 V, allowing the satellite's maximum continuous power consumption to reach 4.5 W. Each solar panel includes a dedicated Maximum Power Point Tracking (MPPT) circuit to maximize power generation.[10]

The battery board contains two 750 mAh Lithium-Ion cells and a battery protection circuit. It facilitates power transfer from the solar panels to the main EPS board. Two inhibit switches on the battery board disconnect the batteries from the negative terminal to the ground, as shown in Fig. 11, as required by launch providers. The battery protection system prevents discharging when voltage drops below 2.8 V and stops charging at 4.2 V or when temperatures reach 0°C (low) or 40°C (high). A known issue with the bypass diodes in the protection MOSFETs can cause a voltage drop during low- or high-temperature protection, occasionally resulting in Electrical Power System

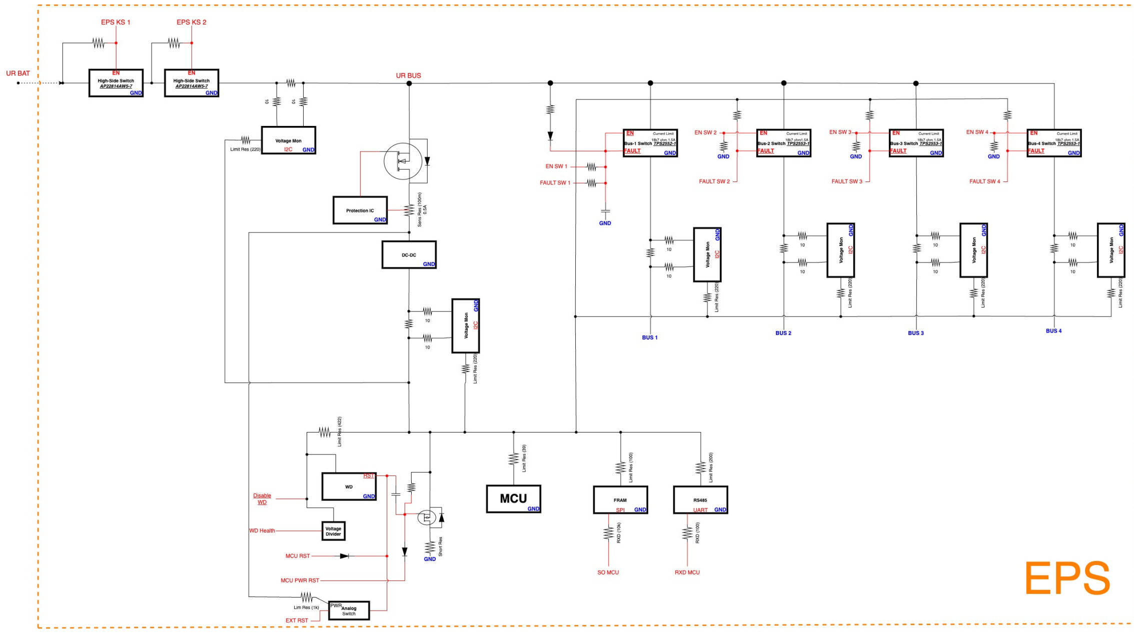

Fig. 7. EPS Block Diagram.

(EPS) brownouts during high-current draws from systems like the COMMS.

The satellite has four solar panels along the X and Y axes, integrated as part of the structure of the satellite. Each panel contains two solar cells, with MPPT circuits for each cell, enabling efficient power monitoring and load balancing. The panels also have cutouts for laser reflectors, temperature sensors, and power monitoring circuits. In-orbit data shows that panel temperatures fluctuated between -40°C and 40°C.

The EPS main board underwent four revisions, with the final version costing €456 for electronics and €213 for PCBs. Likewise, the battery system required four revisions, with final costs of €386 for electronics and €221 for PCBs. The solar panels (four sides) went through three revisions, with the final version costing €308 for electronics and €1061 for PCBs. Additionally, 20 solar cells were procured at a total cost of €7000, with eight cells integrated into the panels. All costs are based on manufacturing five units of each system.

- On–Board Computer - OBC

The On-Board Computer (OBC) serves as the satellite central processor, interfacing with the different subsystems and handling data acquisition and storage. Its architecture is based on the core design (Fig. 6), with the addition of a micro-SD card for mass data storage, featuring an additional protection system and a voltage level converter (Fig. 8).

The OBC also includes a 40-pin daughter-board connector, which supports future payload developments, providing one unregulated bus, one Inter-Integrated Circuit (I2C) line, two optional I2Cs, two optional Serial Peripheral Interfaces (SPIs), and various analog and digital pins. Initially, a Global Navigation Satellite System (GNSS) payload was planned but, due to the late delivery of the item during the 2020 COVID lockdown, the receiver was omitted and such payload was adapted to serve as a secondary OBC. The subsystem design allows for over-the-air complete software updates, enabling future operational enhancements and bug corrections.

The OBC is the system closest to the subsystem core: it went

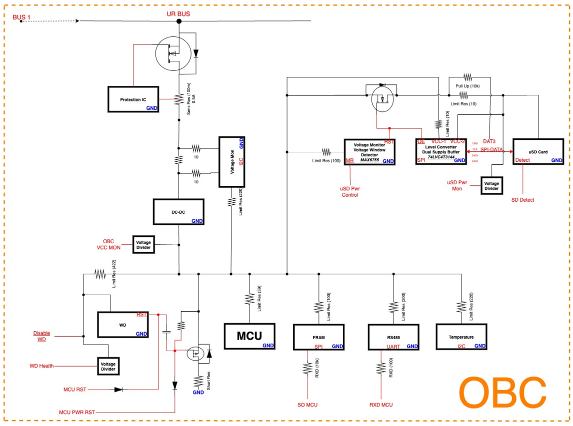

Fig. 8. OBC Block Diagram.

through two revisions, with an initial revision (revision 0) repurposing the Attitude Determination and Control System (ADCS) module. The final revision of the OBC costs 388 € for the electronic components and 99 € for the Printed Circuit Boards (PCBs) for a total of 97 € per unit (while producing five of them at once).

- Communication System - COMMS

The Communication System (COMMS) system consists of three modular boards, enhancing modularity and easing system updates. The first is the receiver/transmitter board, which interfaces directly with the satellite bus to handle modulation and demodulation; it also incorporates two integrated circuits (SX1276 from Semtech) for signal modulation and demodulation and an MCU to encode and decode the bit-stream, allowing the protocol flexibility suited for an educational mission. The second board hosts the power amplifier, which includes a 1 W Radio Frequency (RF) peak power amplifier (RFPA0133 from Qorvo) that can operate at different power levels, providing an efficiency between 55–65%. This board also houses a Low-Noise Amplifier (LNA) to boost receiver sensitivity, enabling full-duplex operations. Both of these boards are shown in Figure 9.

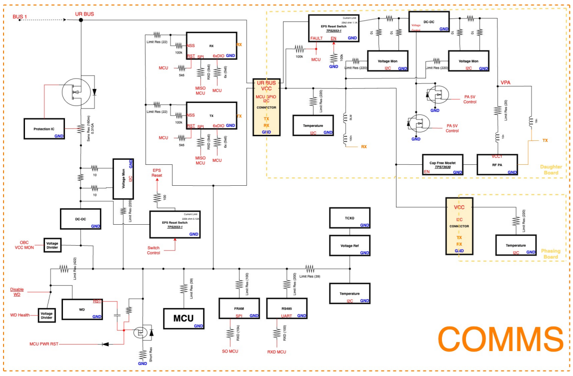

Fig. 9. COMMS Block Diagram.

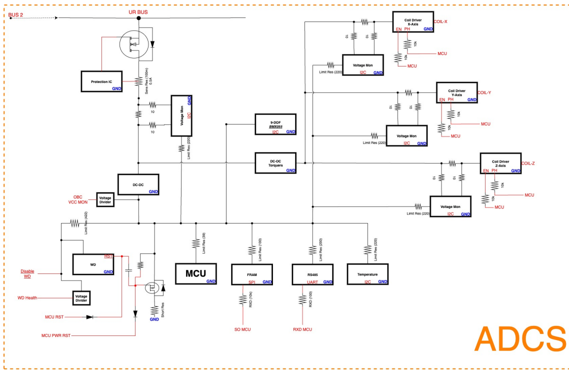

Fig. 10. ADCS Block Diagram.

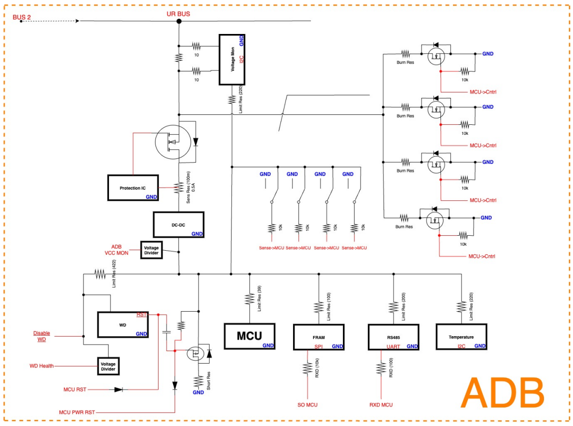

Fig. 11. ADB Block Diagram.

The third component is the antenna phasing board, positioned at the satellite's edge, connecting individual antenna elements to create the necessary radiation patterns for uplink and downlink. The antenna system includes a low-frequency antenna (operating between 500 kHz and 10 MHz), a monopole for uplink at 145 MHz, and a dipole for downlink at 435 MHz, as well as GNSS antennas for GPS L1 and L2 bands. Designed for compactness, this board uses MMCX connectors as rotating elbows, ensuring the antennas can be stowed securely during launch and deploy in orbit upon command.[11,12]

The main communication board underwent three revisions, with the final version costing 384 € for the electronic components and 120 € for PCBs. The power amplifier board, also known as the COMMS DB, went through two revisions, with the final version costing 384 € for the components and 90 € for PCBs. Lastly, the Antenna Phasing Board (APB) had two revisions, with the final version costing 252 € for electronics and 111 € for PCBs. Five units of each system were initially produced for a cost of 268 € per board.

- Attitude Determination and Control System - ADCS

The ADCS is designed to reduce satellite post-deployment tumbling using magnetic torquers, providing a coarse pointing accuracy of approximately 20°, though this level of precision is not essential for the onboard systems.[13] The ADCS includes a Bosch BMX055 Inertial Measurement Unit (IMU) with a 3-axis magnetometer, accelerometer, and gyroscope for sensing and three air-core torquers for actuation. In Figure 10, a block diagram of the ADCS is shown.

Two revisions of the ADCS were produced. The final revision cost 474 € for electronic components, 163 € for PCBs, 281 € for the 3D–printed torquer structures, and 27 € for the copper wire used in the windings. Although five boards were manufactured, only one set of coils was produced and launched with the satellite, for total cost per-board of 814 €.

- Antenna Deployment System - ADB

The antenna system is too large to fit on the spacecraft in its operational configuration when inside the deployment canister. Therefore, the four monopoles must be deployed by the antenna deployment board, which uses thermal knives to release each monopole sequentially. The OBC initiates this deployment sequence 15 minutes after satellite release to avoid interference with the launcher or collisions with other payloads. In addition to the core elements, this system includes four switches to control the deployment of the antennas and sensors for the deployment of the antennas, shown in Figure 11.

Three revisions of the Antenna Deployment Board (ADB) were manufactured, with the final version costing 412 € for the electronic components, 180 € for PCBs, 2270 € for antennas (gold plated, 3 mm diameter brass tubes), and 2500 € for the antenna deployment springs. Five boards were produced at a cost per board of 1072 €.

4. Cost Analysis of Delfi-PQ

Building every subsystem around the same core enables agile and cost–effective development: each revision on any subsystem directly solves the problems and makes it possible to implement additional improvements. Although the subsystems were based on the "core" design, they still required multiple revisions: throughout the development cycle various production cycles occurred, eight in 2017, eleven in 2018, five in 2019 and fifteen in 2020. In these development cycles for the satellite bus, four versions of EPS, four versions of Battery, three versions of Solar Panels, two versions of OBC, ADCS and ADB were developed. In addition to the satellite bus, an additional communication system was manufactured for the Low-Noise Amplifier (LNA) payload, one version of GNSS, and eight development/test boards were manufactured. Mechanical systems were limited for the satellite: three versions of the satellite structure and two versions of antennas, one of which was the gold–plated flight version, were manufactured.

The total cost of the hardware development, including testing and the tax (Value Added Tax (VAT) is 21% in the Netherlands) of the satellite, is 86.6 k€, from 2017 to 2020. It should

Table 2. Total Satellite Hardware Costs in Euros and Number of Revisions.

System	EPS	Battery	Solar Panels	Comms	Comms DB	Comms PB	GPS	ADB	OBC	ADCS	Structure	Laser Ref.	Payload	Satellite
Mechanical								2500.01		281.45	11016.65	2822.51		
Electronics	3871.26	2115.42	10644.77	3145.27	1019.68	546.34	8071.41	1141.39	1295.84	639.90			495.42	9470.28
PCB	750.02	1223.49	3899.35	1187.80	444.09	414.63	280.60	674.05	599.43	853.53				240.25
# Revisions	4	4	3	2	2	2	1	2	2	2	3	1	1	

be noted that each electronics production run included enough components to produce five systems. For higher-level internal budget tracking, four labels were established: *support*, which includes general hardware, software, and additional jigs for other subsystems; *mechanical*, covering structural pieces, antennas, screws, and other mechanical components; *electronics*, encompassing electronic components for subsystems; and finally, *PCB*, which includes PCBs and stencils for subsystems. Figure 12 shows the percentage breakdown of each label contribution to the final cost: *support* accounts for 7124 €, *mechanical* for 23416 €, *electronics* for 44007 €, and *PCB* for 11605 €. Detailed cost breakdowns of the subsystems are given in Table 2.

A yearly expenditure is shown in Figure 13: the initial high expense in 2017 was due to the development of the early models and the improvement of the subsystem core. Later in 2018, systems were tested, and initial versions of most subsystems were developed by the end of 2018. The total amount spent was approximately 43 k€. In 2019, the system development slowed down due to COVID regulations and limited office hours: expenses related to the support equipment have increased thus increased as the team focused on building satellite setups that can be connected remotely, allowing students and the team to write new software, debug, and improve the systems. Yearly, 10 k€ was spent, making the total 53.75 k€ by the end of 2019. As

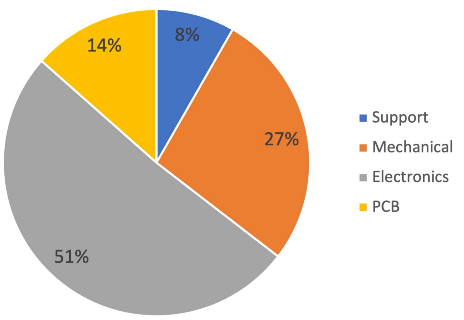

Fig. 12. Cost Breakdown of Delfi-PQ.

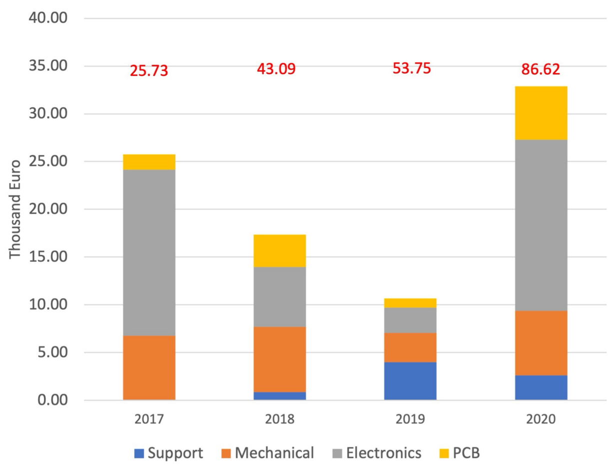

Fig. 13. Cost per year of Delfi–PQ. Numbers in RED are the cumulative cost of the satellite throughout the years.

COVID regulations became the new normal and access to offices was arranged, the amount of time spent in the laboratory increased: 2020 was also the year when the satellite had been delivered for launch: as a result, final and flight versions of the systems were being developed. The sudden increase in the PCB and electronics expenses occurred as a result of this delivery time. In 2020, 32.87 k€ were spent, making the grand total of the hardware costs 86.63 k€. After 2020, the satellite was delivered, and there were no additional costs related to hardware development.

A factor that needs to be taken into account is the experience of the developers: the team has more than 30 years of combined experience, which is another factor that drives the cost down. The total cost of 86 k€ includes multiple revisions and multiple boards during the same revision. When an institution plans to start building its own space program, it should take into account these development costs.

Building a satellite based on Delfi-PQ systems, a single flight model with an engineering model could be constructed for approximately 25 k€, as shown in Table 3. Additionally, the costs for some additional structural pieces such as laser reflectors, and solar cells were 9015 €, 910 €, and 7000 €, respectively. Adjusting for semiconductor price inflation of 6.4% from December 2020 to December 2023,[14] and including The Netherlands 21% VAT, the estimated cost of producing an equivalent satellite with the same functionality would be approximately 27 k€.

Table 3. Cost Breakdown for Final Revisions of Subsystems

Subsystem	**Electronics (€)**	**PCB (€)**	**Mechanical (€)**
ADCS	474.86	163.4	281
ADB	412.5	180.15	2500
Comms	384.16	120.3	-
Comms DB	353.91	90.75	-
Comms PB	252.87	111.65	-
EPS	456.6	213.85	-
Battery	386.17 + 2800	221.35	-
Solar Panels	308.1	1061.25	-
OBC	388.57	99.05	-

5. Conclusion and Future Work

This paper presents briefly the design of Delfi-PQ, a 3P PocketQube developed by the Delft University of Technology and it later presents breakdown of the costs the team has sustained to produce the flight module of the satellite. The mission was developed as part of the educational curriculum in Aerospace Engineering between 2017 and 2020. The satellite, while being only 50x50x178 mm and having a mass of 545 g, shares the same problems and requirements of bigger satellites. Delfi–PQ was launched on January 13th 2022, and stayed operational till it naturally re-entered in the atmosphere on January 9th 2024.

This paper provides a comprehensive examination of the design, development, and associated costs of Delfi–PQ, serving as a valuable resource for teams undertaking similar projects.

By offering a detailed breakdown of the costs by systems, components, structural elements, and subsystems, the paper aims to support more accurate cost modeling for future satellite endeavors. Only hardware costs for the satellite flight model are presented: this excludes on purpose all personnel costs, as most of the activities have been carried out by students at the Delft University of Technology. Moreover, only the last revision of all satellite components is presented (and detailed costs for all the preliminary design phases have been omitted). This structured approach not only aids in budgeting and planning but also establishes a foundational reference for institutions planning their own satellite missions, enabling them to build upon Delfi–PQ framework and insights.

A new 3P PocketQube, incorporating both the experience gained from Delfi–PQ and additional improvements on legacy subsystems, is estimated to cost at least 27 k€ to procure. This budget covers the production of five units for each subsystem, along with two complete sets of solar panels (including solar cells) and two structural systems. This setup enables the construction of one flight model and one engineering model, with additional spare systems available for ground testing and future educational purposes. All design and assembly costs, together with the costs of laboratories and support facilities, is not included and it would make the cost estimate too dependent on specific local institutions.

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