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DOTTORATO DI RICERCA IN INGEGNERIA INDUSTRIALE

CICLO XXXVII

NEW PARADIGMS FOR THE INNOVATION IN DESIGN AND OPTIMISATION OF
MECHANICAL AND LOGISTICS SYSTEMS

Coordinatore:
Chiar.mo Prof. Gianni Royer Carfagni

Tutore:
Chiar.mo Prof. Andrea Volpi

Dottorando: Michele Bocelli

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A Emma e Ludovico,

*Guardate il mondo da diverse Prospettive,
senza mai dimenticare quale sia il Vostro Punto di Vista.*

*A volte la differenza tra il successo e la sconfitta,
nello spazio o forse nella vita,
sta davvero in un capello,
ma del materiale giusto.*

Eng. Tommaso Ghidini, Ph.D.

Abstract

This Ph.D. Thesis delves into the critical role of Innovation across various sectors, emphasizing its significance not only in Industrial Engineering but also in any field where technological advancement and operational efficiency are paramount. Innovation is portrayed as a necessity, rather than merely an opportunity, to address both current and future challenges. The research is organized into three main phases: idea generation, simulation, and experimentation, each of which is explored through in-depth case studies. The first contribution focuses on the evaluation of ideas within an Open Innovation framework. In today's competitive landscape, companies must actively engage with external sources of creativity to enhance their innovation potential. A novel method is proposed that combines qualitative and quantitative criteria, facilitating the selection of the most promising ideas and fostering collaboration among diverse stakeholders. The second contribution addresses the optimization of warehouse picking processes using discrete-event simulation techniques. This work solves a classic logistics challenge by applying a simulation tool to optimize warehouse layouts, reduce travel times, and improve the overall use of resources. The third contribution centers on experimentation under altered gravity conditions, conducted during parabolic flight campaign. The behavior of a pulsating heat pipe was analyzed in micro-gravity, hypergravity and normal-Earth gravity conditions, yielding critical insights for the development of advanced space technologies. In conclusion, this Thesis presents innovative approaches applicable to various real-world scenarios, from enhancing decision-making in Open Innovation, to optimizing logistics, and advancing the design of technologies for space exploration.

Dichiarazione

 Questa Tesi costituisce parte della ricerca condotta dal sottoscritto durante il percorso di Dottorato di Ricerca in Ingegneria Industriale iniziato a Novembre 2021 e terminato ad Ottobre 2024.

L’Innovazione ha rappresentato la tematica principale del mio percorso, declinata non solamente nello sviluppo di nuovi prodotti ma anche nello sviluppo e ottimizzazione di processi e metodologie, sia ingegneristiche, ma anche non strettamente tecniche, con l’obiettivo di migliorare l’efficienza e l’efficacia dei sistemi.

Il focus del mio progetto di ricerca è stato quindi l’analisi critica dei paradigmi esistenti, al fine di poter creare nuove metodologie applicabili a differenti realtà, che tuttavia risultano unite dalla necessità di adottare metodi più efficienti di progettazione, controllo e ottimizzazione.

Tengo a precisare che i contenuti di tale elaborato rappresentano una

 This Thesis is part of the research I carried out during the Ph.D. program in Industrial Engineering, which started in November 2021 and concluded in October 2024.

Innovation has been the central theme of my journey, not only in the development of new products but also in the development and optimization of processes and methodologies, both engineering-related and non-technical, with the aim of improving the efficiency, effectiveness, and overall performance of systems.

The primary focus of my research project has been the critical analysis of existing paradigms, with the aim of creating new methodologies applicable to different scenario and contexts, all of which share a common need to adopt new and more efficient methods of design, control, and optimization.

I would like to emphasize that the contents of this thesis represent only a portion of the research I conducted

parte di quella che è stata la ricerca da me condotta durante il mio percorso di Dottorato di Ricerca; oltre ad ampliare le mie conoscenze e competenze in ambito Impianti Meccanici, ho avuto la possibilità di approfondire tematiche affini al mio settore disciplinare di afferenza: Impianti Industriali Meccanici (IIND-05/A).

I risultati di quella che è stata la ricerca da me condotta sono tangibili dalla mia partecipazione a progetti regionali (SMART H_2O), nazionali (TOP, SPUMA) e internazionali (DEPLOY! Project, ISS-FPPHP); dalle pubblicazioni scientifiche di cui sono autore o co-autore (4 su riviste scientifiche internazionali e 12 atti di conferenza); oltre che essere un membro fondatore dello Spin-off accademico Ulisse-Solutions S.r.l.

Il presente lavoro è organizzato in quattro capitoli principali, preceduti da una introduzione generale. Nel primo capitolo viene descritto il processo di generazione e validazione di un'idea, adottando un approccio basato sull'Open Innovation. Il secondo capitolo si concentra sull'analisi di differenti scenari tramite l'utilizzo della metodologia ad elementi discreti, approfondendo le modalità di valutazione.

during my Ph.D. In addition to expanding my knowledge and expertise in Mechanical Plants, I had the opportunity to delve into various related and complementary topics within my field, namely Industrial Mechanical Plants (IIND-05/A).

The results of my research are evident in my participation in regional (SMART H_2O), national (TOP, SPUMA), and international projects (DEPLOY! Project, ISS-FPPHP), as well as in the scientific publications of which I am the author or co-author (4 in international scientific journals and 12 conference proceedings), and in my role as a founding member of the academic spin-off Ulisse-Solutions S.r.l.

This work is organized into four main chapters, preceded by a general introduction, each designed to address specific aspects of the research conducted and to provide a comprehensive understanding of the methodologies and findings. The first chapter describes the process of idea generation and validation, adopting an Open Innovation-based approach. The second chapter focuses on the analysis of different scenarios through the use of discrete event simulation, providing an in-depth evaluation. The

Il terzo capitolo, invece, affronta la progettazione di un esperimento e il relativo test condotto in condizioni di gravità alterata. Infine, nel quarto capitolo, vengono presentate la discussione generale, le conclusioni emerse dal lavoro svolto, e vengono delineati i possibili sviluppi di ricerca futuri.

Si ripropongono nel diagramma di flusso (Figure 1) i tre step di sviluppo con metodi innovativi da me affrontati nel percorso di Dottorato di Ricerca.

third chapter addresses the design of an experiment and its testing under altered gravity conditions. Finally, the fourth chapter presents the general discussion, conclusions taken from the work and outlines potential future developments of the research.

A flowchart (Figure 1) presents the three innovative development steps that I addressed during my Ph.D. program.

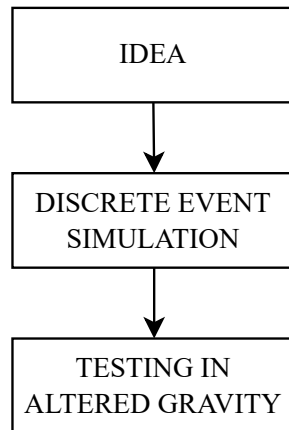


Figure 1: Steps of development with innovative methods.

Ringraziamenti

*A chi non ho avuto la fortuna di conoscere,
A chi c'è stato dall'inizio,
A chi ho incontrato lungo la strada,
A chi ha percorso con me solo una parte di questo cammino,
A chi ha scelto una direzione differente rispetto alla mia,
A chi mi accompagnerà fino al traguardo.*

Grazie

*Per trasformare ogni giorno di questo Viaggio in un'esperienza Straordinaria.
Se sono la persona che Sono, il Merito è Soprattutto*

Vostro

Michele Prulli

Premessa

■ ■ L'evoluzione della produzione industriale dalla fine dell'Ottocento ai giorni nostri si configura come una serie di cambiamenti radicali e paradigmatici (Smith, 2020), che hanno trasformato profondamente sia le modalità di progettazione che di produzione.

All'inizio di questo percorso si ha una fase di produzione artigianale, in quanto predominante forma di produzione del *XIX* secolo, caratterizzata da maestranze altamente specializzate e metodi di produzione su scala ridotta.

La transizione verso la produzione meccanizzata, segnò una svolta epocale. L'avvento del taylorismo, caratterizzato dall'applicazione di metodi scientifici per ottimizzare la produzione e generare un significativo aumento della produttività (Taylor, 1911).

Il modello di produzione di massa, incarnato da Henry Ford attraverso il fordismo, rappresentò un ulteriore

🇬🇧 The evolution of industrial production from the late *XIX* century to the present day is characterized as a series of radical and paradigmatic changes (Smith, 2020), that have radically transformed both design and production methods.

At the beginning of this journey, there is an initial phase of artisanal production, as it was the predominant form of production in the *XIX* century, characterized by highly skilled labor and small-scale production methods.

The transition to mechanized production marked an historical change. The advent of Taylorism, characterized by the application of scientific methods to optimize production and generate a significant increase in productivity (Taylor, 1911).

The mass production model, embodied by Henry Ford with Fordism, represented another evolutionary leap. The introduction of the assembly line

salto evolutivo. L'introduzione della catena di montaggio e l'ottimizzazione dei processi produttivi, oltre che la standardizzazione dei prodotti, permisero la produzione in massa di beni di consumo a prezzi accessibili. Questo processo fu esemplificato dalla celebre frase riguardo al colore della vettura Ford Model T (Figure 2): *Qualsiasi cliente può avere un'auto dipinta del colore che desidera, purché sia nera* (Ford, 1922).

and the optimization of production processes, along with the standardization of products, allowed for the mass production of consumer goods at affordable prices. This process was exemplified by the famous phrase regarding the color of the Ford Model T (Figure 2): *Any customer can have a car painted any color they want, as long as it is black* (Ford, 1922).

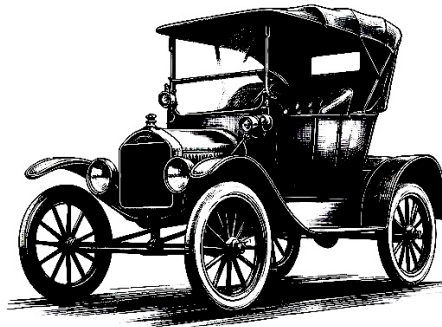


Figure 2: Ford Model T, produced from 1908 to 1927.

Negli anni successivi, l'avvento del toyotismo (Toyota Production System, *TPS*), rivoluzionò ulteriormente il paradigma produttivo, focalizzandosi sull'eliminazione degli sprechi, sulla flessibilità produttiva e sul coinvolgimento attivo dei lavoratori nella risoluzione dei problemi (Ohno, 1988).

In the following years, the advent of Toyota Production System (*TPS*), further revolutionized the production paradigm, focusing on waste elimination, production flexibility, and the active involvement of workers in problem solving (Ohno, 1988).

With the digital era and the ad-

Con l'era digitale e l'avvento dell'Industria 4.0, attraverso l'introduzione di tecnologie avanzate come l'Internet delle cose, l'Intelligenza Artificiale e la Stampa 3D, il panorama industriale è stato nuovamente rivoluzionato. L'efficienza e la personalizzazione convergono, consentendo la produzione su misura e evidenziando una tendenza verso la customizzazione del prodotto.

Negli ultimi anni, si è assistito all'emergere di nuove tipologie di paradigmi nell'industria produttiva, in particolare ancora una volta, nell'industria automobilistica si è affermato il teslismo (Browne et al., 2020). Grazie a questo nuovo paradigma si verifica quindi una accelerazione nell'innovazione attraverso l'elettrificazione, l'automazione avanzata e una costante ricerca di nuovi orizzonti innovativi. Il teslismo, introdotto come un approccio rivoluzionario, ha trasformato ulteriormente un settore all'apparenza già saturo, introducendo nuovi sistemi avanzati di assistenza alla guida e innovativi modelli di business basati sulla connettività e la condivisione.

Nell'arco temporale di un secolo, i paradigmi industriali sono stati rivoluzionati più volte, testimoniando la

vent of Industry 4.0, through the introduction of advanced technologies such as the Internet of Things, Artificial Intelligence, and 3D Printing, the industrial landscape has been revolutionized once again. Efficiency and personalization converge, enabling tailored production and highlighting a trend towards product customization.

In recent years, new types of paradigms have been emerging in the manufacturing industry, particularly once again in the automotive industry, where the Teslism paradigm has appeared (Browne et al., 2020). Thanks to this new paradigm, there has been an acceleration in innovation through electrification, advanced automation, and a constant search for new innovative horizons. Teslism, introduced as a revolutionary approach, has further transformed an apparently saturated sector, introducing advanced driver assistance systems and innovative business models based on connectivity and sharing.

Over the course of a century, industrial paradigms have been revolutionized multiple times, demonstrating the extraordinary speed at which the industry transforms and evolves (Dahlman and Pomerantz, 2019).

In light of these considerations, the

rapidità con cui l'industria si trasforma e si evolve (Dahlman e Pomerantz, 2019).

Alla luce delle considerazioni espresse, si propone l'immagine della bicicletta per enfatizzare il concetto di dinamicità, sottolineando l'importanza del cambiamento e dell'adattamento necessari per mantenere l'equilibrio. Proprio come il ciclista deve continuamente correggere la sua traiettoria durante la corsa per mantenere l'equilibrio, un'azienda deve adattarsi in modo proattivo alle fluttuazioni del mercato, alle innovazioni tecnologiche e alle mutate esigenze dei clienti. Questo dinamismo è essenziale per affrontare le sfide e cogliere le opportunità, richiedendo un monitoraggio costante delle variabili interne ed esterne e l'implementazione di strategie *smart*. Solo così sarà possibile garantire la sostenibilità e la competitività nel lungo termine.

Il dinamismo, in questo contesto, si configura quale motore propulsivo non solo per l'Azienda stessa, ma in un contesto più ampio, anche per l'intera Umanità, fungendo da catalizzatore per l'avanzare verso il Futuro. La Staticità è l'antitesi della crescita. Così come la bicicletta (Figure 3) ha bisogno di movimento per mantener-

l'immagine di una bicicletta è proposta per enfatizzare il concetto di dinamismo, sottolineando l'importanza del cambiamento e dell'adattamento necessari per mantenere l'equilibrio. Proprio come il ciclista deve continuamente correggere la sua traiettoria durante la corsa per mantenere l'equilibrio, un'azienda deve adattarsi in modo proattivo alle fluttuazioni del mercato, alle innovazioni tecnologiche e alle mutate esigenze dei clienti. Questo dinamismo è essenziale non solo per affrontare le sfide e cogliere le opportunità, richiedendo un monitoraggio costante delle variabili interne ed esterne e l'implementazione di strategie *smart*. Solo così sarà possibile garantire la sostenibilità e la competitività nel lungo termine.

Dynamism, in this particular context, serves as a crucial driving force that propels not only the company itself but also, in a broader sense, the whole of humanity forward, acting as a catalyst that facilitates the journey into the future. The concept of stillness stands in stark contrast to the principle of growth. Just as a bicycle (Figure 3) requires continuous movement to maintain balance and avoid falling off, an entrepreneur-

si in equilibrio, un'organizzazione imprenditoriale deve avanzare costantemente per preservare la sua posizione competitiva. Dinamicità ed Equilibrio diventano quindi elementi essenziali per raggiungere il successo in un contesto in continua evoluzione.

rial organization must take a proactive approach and continuously progress to maintain its competitive position in an ever-changing marketplace.

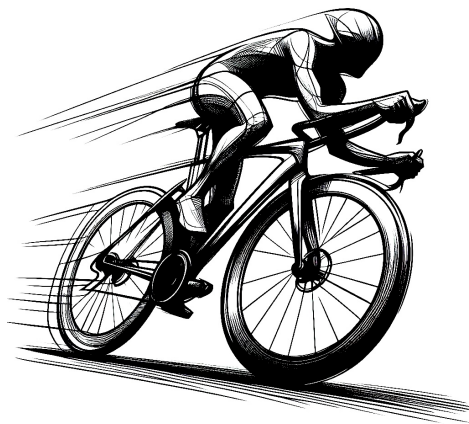


Figure 3: The bicycle as a symbol of dynamism and balance.

Il Dinamismo, nell'ambito della necessità di continua Innovazione, può implicare anche cambiamenti radicali di paradigmi consolidati nel tempo. Emerge di conseguenza la cruciale importanza dell'azione e della decisione. L'approccio *Fail fast, fail cheap, fail early* (Ries, 2011), caratteristico nelle start-up della Silicon valley, sottolinea la necessità di sperimentare, imparare dai fallimenti e iterare rapidamente verso il successo. Nell'affrontare la sfida posta dell'Innovazione, ci si im-

Dynamism, in the context of the continuous need for Innovation, can also imply radical changes to established paradigms over time. Consequently, the crucial importance of action and decision-making emerges. The approach *Fail fast, fail cheap, fail early* (Ries, 2011), characteristic of Silicon Valley start-ups, emphasizes the necessity to experiment, learn from failures, and iterate quickly towards success. When facing the challenge posed by Innovation, one inevitably encoun-

batte obbligatoriamente nell'*Angoscia* della scelta (Kierkegaard, 1844), generata dalla consapevolezza delle infinite possibilità e delle incertezze connesse alle decisioni. L'*Angoscia* è il sentimento del possibile, la condizione esistenziale generata dalla *vertigine* della libertà, ovvero dalle infinite possibilità dell'esistenza. Tuttavia, è solamente tramite l'assunzione di responsabilità nelle decisioni e la considerazione dei fallimenti come tasselli fondamentali del processo, che sarà possibile sfruttare efficacemente il potenziale trasformativo dell'*Innovazione*.

ters the *Anxiety* of choice (Kierkegaard, 1844), generated by the awareness of infinite possibilities and the uncertainties associated with decisions. *Anxiety* is the feeling of the possible, the existential condition generated by the *vertigo* of freedom, or the infinite possibilities of existence. However, it is only through taking responsibility for decisions and considering failures as fundamental building blocks of the process that it will be possible to effectively harness the transformative potential of *Innovation*.

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Chapter 0

General Introduction

E pur si muove.

And yet it moves.

Galileo Galilei

Innovation is widely recognized as one of the main drivers of technological, economic, and social progress. Joseph Schumpeter (Schumpeter, 1934), defined innovation as the essence of *Creative Destruction*, a process that drives economic development by transforming products, processes, and markets. In the realm of Industrial Engineering and technological disciplines, innovation is not merely an opportunity but a strategic necessity to address the challenges of an increasingly complex and interconnected world (Porter, 1985).

Innovation is not only central to economic growth but also to the advancement of scientific knowledge and technological frontiers.

Throughout history, the greatest minds in science, working in diverse contexts and eras, have faced the undeniable need for innovation as a fundamental driver of progress in their research.

Galileo Galilei, in the 16th century, revolutionized our understanding of the universe by challenging the traditional geocentric model. *In questions of science, the authority of a thousand is not worth the humble reasoning of a single individual* (Galilei, 1620). His innovative spirit and willingness to question established norms were essential in shaping modern science.

In the 19th century, Nikola Tesla, with his pioneering work in electrical engineering, recognized that pushing the boundaries of conventional thought was crucial for scientific breakthroughs. *The scientists of today think deeply instead of clearly. One must be sane to think clearly, but one can think deeply and be quite insane*, (Tesla, 1919), underlining the importance of thinking unconventionally to bring about true innovation.

Similarly, Louis Pasteur, whose discoveries in microbiology laid the foun-

dation for modern medicine, understood that success in science was grounded in preparedness. *Fortune favors the prepared mind* (Pasteur, 1857), highlighting that being ready to seize opportunities in innovation was key to advancing knowledge and solving critical health challenges.

In the early 20th century, Albert Einstein revolutionized physics with his theory of relativity and insisted on the value of curiosity and continuous questioning in the pursuit of knowledge. *The important thing is not to stop questioning. Curiosity has its own reason for existing* (Einstein, 1955). Einstein's work embodies the idea that progress in science relies heavily on a constant drive for deeper understanding.

Echoing this sentiment, Max Planck observed that scientific progress often comes through the challenging of entrenched ideas, noting: *Science advances one funeral at a time* (Planck, 1949). His comment reflects how innovation in science is often resisted until new perspectives finally replace the old.

In the latter half of the 20th century, Stephen Hawking highlighted the importance of adaptability in science, *Intelligence is the ability to adapt to change* (Hawking, 2007). His work on black holes and cosmology reshaped our understanding of the universe and underscored the essential role of innovation in scientific discovery.

Finally, Vannevar Bush emphasized the vital connection between science and progress, *Science and technology are the engines of prosperity in a modern economy* (Bush, 1945). His statement reinforces the idea that scientific and technological innovation not only pushes forward knowledge but is also crucial for economic and social development.

Thus, from Galilei's challenge of ancient beliefs to Hawking's exploration

of the cosmos, these iconic figures, spanning centuries, demonstrate that innovation is a timeless and universal force, essential for advancing science and solving the complex problems of each era. Innovation, by its very nature, often challenges the conventional wisdom and established norms. As history has shown, groundbreaking ideas can disrupt long-standing paradigms and force society to reconsider what was once considered undeniable. It is precisely this ability to challenge the status quo that allows innovation to drive progress, even when it goes against the grain of prevailing thought.

Drawing on the concepts discussed earlier, this Ph.D. Thesis examines Innovation as a dynamic and integrated process, organized into three main key phases. These phases — *idea generation*, *process simulation*, and *technological experimentation* — are designed to address complex challenges by combining theoretical insights with practical applications. Through this framework, this work examines how Innovation unfolds not only in the realm of Industrial Engineering but also in a broader context, highlighting the critical role of interdisciplinary approaches in solving *real-world* problems. Each phase unfolds sequentially as a step in the development process, with each building on the results of the previous one. Though distinct and self-contained, these phases are interconnected by a clear and coherent progression that reflects the broader innovation journey, from the initial spark of creative ideas to the *real-world* testing of technological solutions. This structured approach ensures that the innovations developed are both impactful and adaptable across diverse sectors.

The first contribution of this Thesis focuses on the *evaluation of ideas* within the context of Open Innovation. Chesbrough (Chesbrough, 2003a) in-

troduced the concept of Open Innovation as a model where companies break away from rigid internal innovation boundaries to leverage external sources of creativity, thereby enhancing their innovative potential. However, this openness introduces complexities in the selection and evaluation of ideas, which often originate from diverse stakeholders. To tackle this challenge, a structured framework was developed that integrates qualitative and quantitative criteria, facilitating the selection of the most promising ideas while promoting collaboration among the various actors involved. This dynamic approach considers market evolution and business needs, demonstrating how strategic management of creative resources can transform incremental innovations into radical ones (Tidd et al., 2005).

The second contribution centers on optimizing logistics processes by addressing the *Traveling Salesman Problem* in warehouse picking operations. Logistics is an area where process innovation can generate substantial savings in costs and resources (Rushton et al., 2017). This Thesis developed a tool based on discrete-event simulation to optimize warehouse layouts and enhance picking efficiency by accounting for hardware and software parameters. This integrated approach highlights how modeling and simulation can support decision-making, reduce travel times, and improve resource utilization Law and Kelton, 2007.

Lastly, the third contribution explores *technological experimentation under altered gravity conditions*, a crucial domain for advancing aerospace technologies. Parabolic flight campaigns provide a unique opportunity to study the behavior of physical systems under microgravity and hypergravity conditions, yielding essential data for the development of space technologies

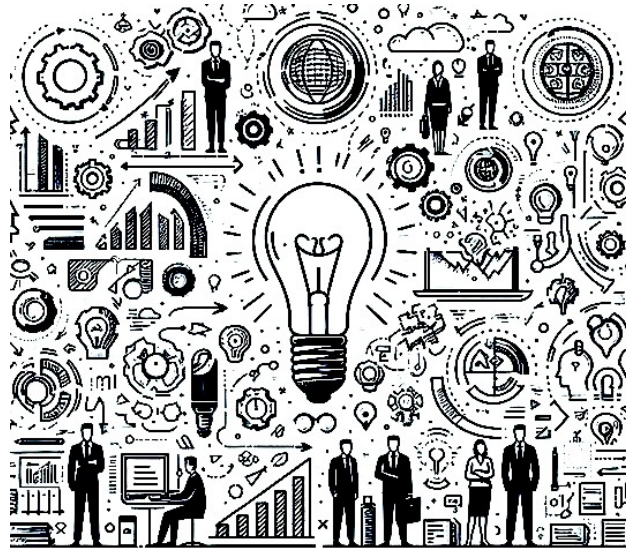
(Clément, 2011). In this study, the behavior of a Pulsating Heat Pipe was analyzed using advanced thermographic techniques and traditional monitoring methods, yielding key insights for designing heat exchangers for both space missions and terrestrial applications Groll and Khandekar, 2004.

This Thesis proposes an interdisciplinary and integrated approach that combines idea generation, simulation, and experimentation to address complex problems and foster innovation in advanced technological contexts. The practical implications are manifold: from optimizing decision-making processes within Open Innovation frameworks to improving logistics operations and designing advanced technologies for extreme environments such as space.

As emphasized by Trott, 2011 and C. M. Christensen, 1997, an integrated approach to innovation is essential to tackling future challenges. Specifically, the ability to combine simulation, experimentation, and *real-world* applications enables the promotion of technological progress in a sustainable and competitive manner.

Chapter 1

Idea Generation



Nomenclature and acronyms

The nomenclature and acronyms used in Chapter 1 are presented in Table 1.1.

Table 1.1: Nomenclature and acronyms used in Chapter 1.

Symbol	Description	Unit
<i>OI</i>	Open Innovation	–
<i>CI</i>	Closed Innovation	–
<i>TOI</i>	Talents for Open Innovation	–
<i>ART-ER</i>	Attrattività Ricerca Territorio - Emilia Romagna	–
<i>KPI</i>	Key Performance Indicator	–
<i>IP</i>	Intellectual Property	–
<i>R&D</i>	Research and Development	–

1.1 Open Innovation

In a global and increasingly connected and dynamic society, knowledge is the main driver of cooperation and collective work (Van Krogh and Roos, 1996); networks created through knowledge sharing have increasingly become a source of ideas and innovation. The concept of innovation has deep roots in the theories of Joseph Schumpeter, who first introduced and considered it a crucial dimension of change (Schumpeter, 1912). In this work, the author observed that increased productivity generated discontinuity and proposed innovation as a source of new industries. Over time, the combination of innovation and new industries has played a key role in accelerating global economic development. In light of this, innovation is identified as the main driver for companies to prosper, grow and maintain high profitability (Drucker, 1988; J. F. Christensen et al., 2005). Citing Heraclitus, 500 BC, *nothing is permanent except change*, even the pre-Socratic philosopher in his view, emphasizes that constant adaptation and innovation are essential for survival and progress principles that remain fundamental to modern business and economic development.

In the innovation journey, the *Idea* is the primary and fundamental starting point (Drucker, 1985). However, the effectiveness and relevance of an idea cannot simply be assumed; rather, it requires rigorous evaluation and selection. In this context, the idea represents the conceptual substrate from which innovative projects, products, or services originate. However, it is essential to subject the idea to a critical analysis to assess its feasibility, sustainability, and potential impact.

Only through a thorough evaluation process and careful selection can an idea turn into a successful initiative and contribute significantly to innovation.

The Open Innovation paradigm (*OI*) radically redefines the way companies approach the innovation process (Wang et al., 2024). Traditionally, innovation was viewed as a Closed Innovation (*CI*), confined within the boundaries of the organization, relying solely on internal resources and expertise. This closed innovation model assumes that the best ideas and talent reside within the company, limiting collaboration with external entities. In contrast, *OI* encourages the integration of external knowledge, recognizing that valuable ideas and innovations can originate from or be implemented by external partners such as universities, start-ups, and other organizations (Wardyn-Runiewicz, 2022). By actively engaging with external stakeholders, such as customers, suppliers, and research institutions, companies are better equipped to respond to the dynamic demands of the market. This approach not only broadens the potential sources of innovation, but also allows firms to leverage external *R&D*, reducing costs and development times. Furthermore, while traditional innovation prioritizes being *first-to-market*, *OI* emphasizes building robust and scalable business models that can effectively exploit both internal and external innovations. In Table 1.2, a comparison between Closed Innovation and Open Innovation is presented, highlighting their distinct characteristics and approaches.

OI is a concept introduced by Chesbrough, 2003b, and represents a strategic approach to research and development for businesses. It involves the collaboration and sharing of ideas and resources with external entities such as

CHAPTER 1. IDEA GENERATION

other companies, academic institutions, and communities.

Table 1.2: Comparison between Closed Innovation and Open Innovation.

Characteristics	Closed Innovation	Open Innovation
<i>Definition</i>	Internal innovation process within the company, developed in isolation.	Process that encourages collaboration with external actors.
<i>Access to Ideas</i>	Limited to internal resources and research and development teams.	Involvement of external partners, customers, and stakeholders.
<i>Intellectual Property</i>	Greater control and protection of intellectual property.	Sharing of intellectual property and co-creation.
<i>Flow of Information</i>	Unidirectional, from the inside out.	Bidirectional, with an exchange of ideas between internal and external parties.
<i>Resources Used</i>	Internal resources for research, development, and innovation.	Utilization of external resources, such as startups, universities, and customers.
<i>Development Time</i>	Longer time to develop ideas and products.	Potential acceleration due to external contributions.
<i>Flexibility</i>	Often rigid, with standardized processes.	Greater flexibility and adaptation to market needs.
<i>Main Objective</i>	Maximize profits and internal efficiency.	Create value through collaboration and shared innovation.
<i>Organizational Culture</i>	Based on secrecy and protection of information.	Promotes transparency and openness to collaboration.

One of the main advantages of *OI* is the acceleration of the innovation process. Actively accepting ideas from external sources provides companies with a constant flow of new concepts, reducing development timelines. Furthermore, this openness leads to a reduction in Research and Development costs, thanks to cost sharing with external partners. Collaborating with stakeholders, defined as “*any group or individual who can affect or is affected by the achievement of the organization’s objectives*” (Freeman, 1984), not

only grants access to specialized expertise but also serves as a catalyst for market expansion. These collaborations enable the development of solutions that are more closely aligned with customer needs, fostering innovation and driving business growth.

However, the implementation of *OI* is not without challenges. One significant issue is the management of intellectual property (*IP*). Companies must balance the protection of their own *IP* with the acquisition and integration of external technologies to remain competitive. Sharing ideas and resources with external entities requires meticulous legal management to avoid intellectual property disputes (Orozco, 2024). The flexible handling of *IP* is critical in this context, as firms need to navigate the complexities of both safeguarding their innovations and leveraging external ones for collaborative advantage.

This first Chapter of this work will describe the key elements of the *OI* framework and the various types of innovation that underpin this approach. Following this overview, the application of the *OI* approach will be presented through a case study focusing on the development of a tool for the collection, evaluation and cataloguing of ideas within a company.

1.1.1 Open Innovation Key elements

The key factors associated with *OI* include several critical elements. These include the identification and acquisition of external ideas, technologies, and competencies, which are essential for fostering innovation and improving internal processes. It is possible to define the key elements of *OI* into five

macro-categories as follows.

- i. **Knowledge In and Out.** Knowledge In (Inside-In) involves acquiring external ideas, technologies, or expertise to develop new products or improve internal processes, while Knowledge Out (Inside-Out) refers to the exploitation of surplus internal resources through licensing, spin-offs, or other commercialization methods.
- ii. **Extended Collaborations.** Actively involving external partners such as suppliers, customers, universities, or startups in the innovation process.
- iii. **Innovation Platforms.** Using platforms or ecosystems that facilitate the sharing and exchange of ideas and resources.
- iv. **Open Approaches to *R&D*.** The company does not rely solely on internal resources for research and development but actively seeks external collaborations to accelerate innovation.
- v. **Open Business Models.** Adopting business models that allow for the monetization of ideas and technologies both within and outside the company.

OI recognizes that ideas and expertise are not confined within corporate boundaries and that access to external sources of innovation can be crucial for competitiveness. This approach enables leveraging the creative potential of a broad network of actors.

A practical example of *OI* is the collaboration between a company and an academic institution for the development of new technologies or participation in incubation and acceleration programmes of startups to stimulate innovation. *OI* has become increasingly relevant in a context where knowledge is dispersed, and technological progress is rapid.

1.1.2 Types of Innovation

In the realm of innovation, three overarching categories often emerge (Figure 1.1).

- i. Incremental Innovation.
- ii. Substantial Innovation.
- iii. Radical Innovation.

Incremental innovation entails gradual and progressive enhancements to existing products, services, or processes (Fasnacht, 2018). It involves small-scale adjustments, optimizations, or updates aimed at refining efficiency, quality, or functionality without fundamentally altering the core elements (e.g. parking sensors). This approach is instrumental in maintaining market competitiveness, addressing evolving customer needs, and streamlining operational processes.

Substantial innovation, also known as sustaining innovation, represents a middle ground between incremental and radical innovation. It involves improvements to existing products or services that provide incremental value to customers (e.g., remote engine diagnostics). Substantial innovation seeks

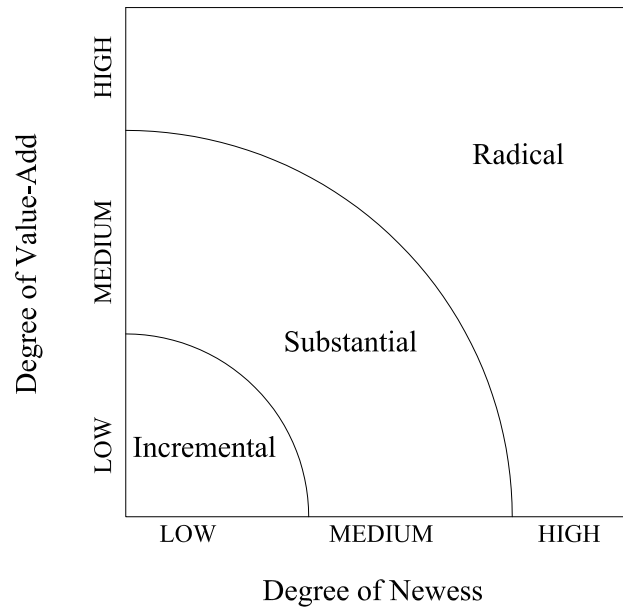


Figure 1.1: Degree of Innovation.

to maintain and extend the competitive advantages of established products, often through enhancements in performance, features, or user experience. As C. M. Christensen and Bower, 1996 emphasize, understanding customer power and strategic investments is essential for firms to avoid failure and capitalize on these improvements. While not as disruptive as radical innovation, substantial innovation plays a crucial role in sustaining market position and profitability over time. Furthermore, Chauca et al., 2021 highlight how disruptive innovation can influence active learning methodologies, illustrating the importance of adapting to evolving market needs and educational paradigms.

Radical innovation, on the other hand, represents a departure from the status quo, involving substantial and revolutionary shifts in the approach to existing products, services, or processes (Holloway et al., 2021). It en-

tails the introduction of entirely new ideas, concepts, or technologies that challenge existing norms and paradigms within an industry (e.g. hybrid engine technology). Radical innovation aims to redefine industry boundaries, disrupt established markets, and create new opportunities for growth and leadership.

These three forms of innovation are not mutually exclusive but rather complement each other within the innovation landscape. Incremental and substantial innovation often serve as precursors to radical innovation, providing a foundation upon which groundbreaking ideas can emerge and flourish. Conversely, radical innovation can inspire further incremental and substantial improvements over time, fostering a cycle of innovation that drives sustained progress and competitiveness in dynamic business environments.

1.1.3 Ideas as Innovation

The foundation of innovation resides in the generation of ideas, which serve as essential catalysts for transformative advancements across various domains. These ideas may originate both from within the organization and from external sources, initiating exploration, experimentation, and development within the scientific and technological landscape. As emphasized by Steve Jobs, attracting and retaining top talent necessitates granting significant decision-making autonomy to employees and prioritizing ideas over hierarchical structures. This perspective underscores that ideas generated by team members are critical to the success of an organization. Jobs also articulated that only the most viable ideas should prevail; otherwise, highly qualified individuals

may feel undervalued and choose to leave the organization. This viewpoint highlights the importance of employee engagement in both the generation and selection of ideas, positioning employees as the primary engine of innovation and corporate advancement. As Plato describes in the allegory of the cave, prisoners perceive a distorted reality, living in illusion (Plato, 380 BC). Similarly, companies that resist embracing *OI* confine themselves to internal resources, thereby limiting growth and adaptability. To remain competitive in a global market, it is imperative for organizations to open themselves to external ideas and insights.

1.2 OI: Case Study

The first Case Study of this thesis is based on the *OI* paradigm.

Specifically, this project involved the collaboration of a multidisciplinary team of six *Ph.D.* researchers, each with their own academic background, with a major pharmaceutical company based in a region of Northern Italy.

The aim of this project was to outline the architecture of a *tool* capable of collecting, storing, and evaluating ideas and proposals for enhancing the company in order to constitute an asset. The target user of this new *tool* should be *potentially anyone within the company*. Thus, it seeks to provide the opportunity for those most familiar with the dynamics and processes, as they utilize them daily, to contribute to the company's growth.

The confluence of varied perspectives within the team acted as a catalyst for enhanced creativity and innovation. The intersection of different academic disciplines sparked a dynamic exchange of ideas, challenging conventional thinking and fostering an environment conducive to the generation of novel solutions. This collaborative dynamic not only accelerated the pace of innovation but also resulted in the emergence of unconventional approaches that might not have been conceivable within a more homogenous team structure.

This collaboration took place under the auspices of the *ART-ER-funded* initiative, *Talents for Open Innovation (TOI)*.

1.2.1 Context and background

In the context of *OI*, where the objective is to access ideas and resources beyond traditional organizational boundaries, a diverse and multidisciplinary team is of crucial importance. Such diversity within the team brings a variety of perspectives, skills, and knowledge that can be leveraged to address innovation problems more comprehensively and creatively.

1.2.1.1 Working Group

In particular, the working group consisted of the following six *Ph.D. researchers* from several departments as well as different Italian universities as reported in Table 1.3.

Table 1.3: Profile of Ph.D. researchers.

Ph.D. course	University
Drug Science	University of Pavia
Industrial Engineering	University of Parma
Economics & Business	University of Cagliari
Aerospace Engineering	University of Bologna
Agriculture & Agrisystems	University Cattolica
Biomedical, Biotech & Translation Science	University of Parma

An heterogeneous and multidisciplinary team is crucial in the context of *OI*. The main advantages of this type of team can be outlined in the following six points.

- i. **Varied perspectives.** Each team member brings unique experiences, training, and ways of thinking. This variety of perspectives allows the

team to examine a problem from multiple angles, increasing the chances of finding innovative solutions (Page, 2007).

- ii. **Complementarity of skills.** Each individual in the team has specific skills and knowledge in their field of expertise. By joining forces, the team can integrate these skills to more effectively tackle complex and multidimensional problems (Hong and Page, 2004).
- iii. **Creativity and innovation.** Diversity within the team stimulates creativity. The interaction between people with different backgrounds can lead to unexpected synergies and the emergence of innovative ideas that may not have been generated in a homogeneous group (Gassmann and Enkel, 2004).
- iv. **Reduction of tunnel vision risk.** In a homogeneous team, there is a risk of falling into *tunnel vision*, focusing on a single perspective or approach to the problem. The presence of members with diverse backgrounds helps to avoid this risk, allowing the team to consider a wider range of options and solutions (Page, 2007).
- v. **Better understanding of customer needs.** A multidisciplinary team can better understand the needs and desires of different customer segments. This deeper understanding can guide the development of products and services that more effectively meet market needs (Gassmann and Enkel, 2004).
- vi. **Greater flexibility and adaptability.** In an *OI* environment, where conditions and opportunities can change rapidly, a multidisciplinary

team is better able to adapt to changes and react flexibly (Gassmann and Enkel, 2004).

1.2.1.2 Company partner

As regards the company partner and principal investigator of the present study, it operates in the biomedical field and is based in Northern Italy, established in the early 2011, swiftly expanded to multinational status within a few years by incorporating Research and Development divisions. Its overarching objective is to transcend its initial role as a mere distributor and evolve into a proactive innovator within the healthcare sector. This trajectory exemplifies its commitment to advancing beyond traditional boundaries, pioneering novel solutions, and driving forward the forefront of healthcare innovation.

1.2.2 Project Description

The challenge posed by the company to the working group was to design a *digital tool* capable of capturing and monitoring all innovation opportunities intercepted by the company and promote internal intrapreneurship by exploiting employees innovative ideas.

Specifically, the tool will have to fulfil three requirements, below mentioned.

- i. Systematically track and archive the entities we engage with in the realm of *OI* (stakeholder analysis).
- ii. Enable internal crowdsourcing for all company members to propose

innovative ideas spontaneously or respond to centrally launched *call-for-ideas*.

iii. Monitoring and standardising the idea implementation process.

The company seeks a radical transformation, shifting towards an open model to unleash its internal innovative potential, thereby creating a permanent *corporate asset*.

The process was carried out in three steps. Initially, a mapping and analysis of the current situation (as-is) was conducted. Subsequently, in agreement with the company, the operational levers to act upon were identified (Design). Finally, a future scenario (to-be) was proposed, describing the optimal solution that emerged based on the previous steps, as shown in Figure 1.2.

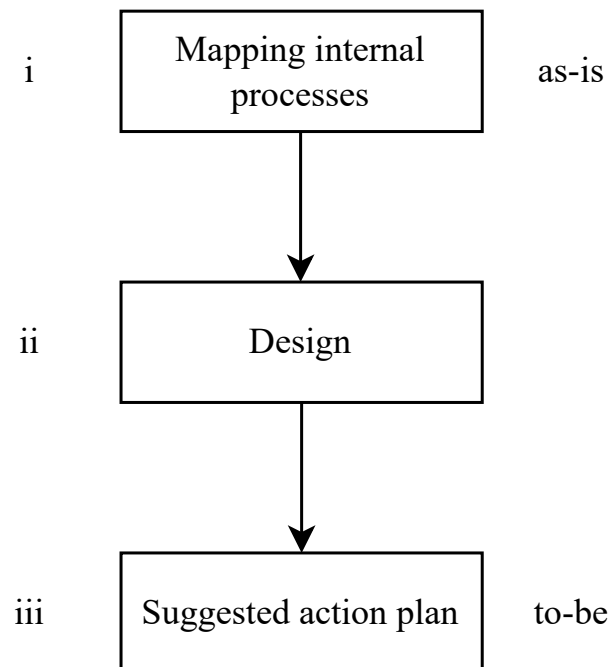


Figure 1.2: Steps of the analysis.

This challenge is actually part of a broader project, defined as the *Innovation Journey*.

In particular, this challenge took place in the first phase, its task was therefore to initiate this innovative process, defined by the company in 5 steps as reported in Figure 1.3.

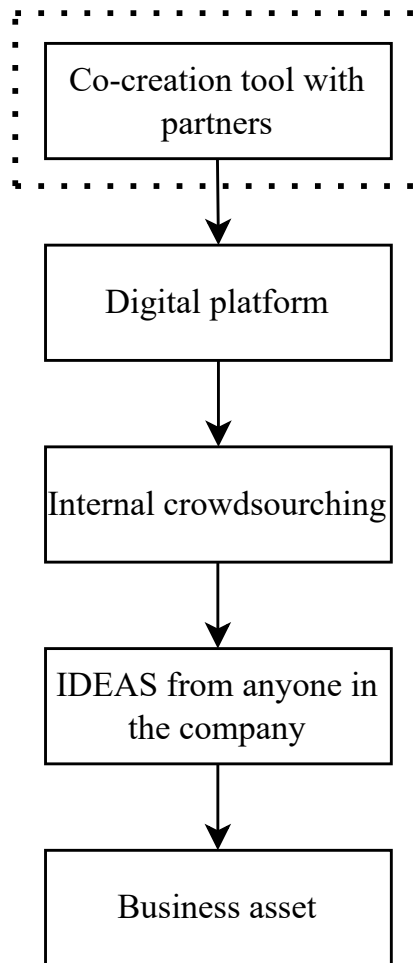


Figure 1.3: Steps of the Innovation Journey.

The company defined this project as an *incremental innovation* and a Business asset, with the potential to drive a *radical transformation* of the entire organization.

1.2.2.1 As-is Scenario

Initially, it was considered essential to conduct a *main stakeholder analysis* as well as a *mapping of internal management and idea-gathering* processes within the company.

Analysing and cataloguing the main internal stakeholders is a crucial step. These stakeholders, being the main users of the tool, must see their needs and expectations reflected in the features and functionality of the *tool*. A correct identification and analysis of the stakeholders makes it possible to create a product that meets the real needs of the company. Below are the four main stakeholder categories identified in the study within the company.

- i. **Field Personnel.** This group consists of individuals who perform active and dynamic tasks directly in the field. They are often on the move and driving. Their work may include home visits, field data collection, and direct collaboration with physicians and healthcare providers in settings such as clinics and healthcare facilities.
- ii. **Office Personnel.** These stakeholders primarily perform static and sedentary tasks, working mainly in offices or on desks. Their responsibilities may include administrative management, resource planning, report preparation, and internal and external communication. They are often involved in data management and the preparation of technical or scientific documentation.
- iii. **Logistics Personnel.** This group lives a mixed professional life between warehouse operations and office work. They manage logistics

and the company's supply chain, coordinating the receipt, storage, and distribution of materials and products. In addition, they handle administrative tasks such as order management, delivery planning, and warehouse documentation.

- iv. **Board.** The board, which includes executives and stakeholders from both internal and external backgrounds, includes the Innovation Committee. The Innovation Committee collaborates in the generation, evaluation, and implementation of innovative ideas aimed at the continuous improvement of services related to the promotion of customer welfare and excellence in corporate welfare.

As for the second point, i.e., mapping internal management and collecting ideas, at the start of the activities, the company already had a preliminary evaluation method in place. This method, as described in Figure 1.4, was a manual and non-automated approach, suitable for managing a small company.

The method implemented within the company is defined by four main steps:

- i. **Idea Identification.** Ideas were primarily sourced from initiatives or contacts related to the company's sector.
- ii. **Internal Committee Review.** Once identified, the ideas were reviewed by an internal committee that met regularly (every two weeks) to analyze and discuss the submitted ideas.

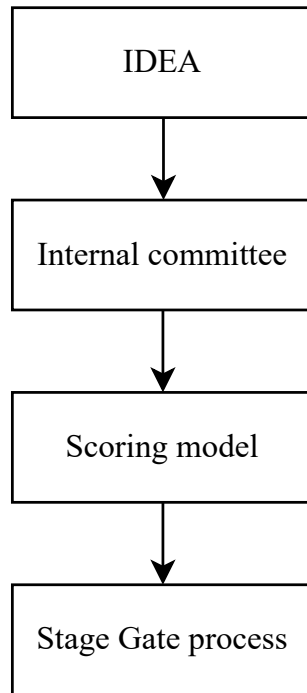


Figure 1.4: Steps of the as-is scenario.

- iii. **Scoring model.** These ideas were evaluated using a set of internally defined Key Performance Indicators (*KPIs*) before initiating the stage-gate process. The evaluation was conducted using a model implemented in an Excel spreadsheet.
- iv. **Stage Gate Process.** After passing the scoring model, the idea was implemented through the stage-gate process (Figure 1.5). In this process, the idea underwent four different levels of review, covering both design and business models. This allowed ideas and innovation opportunities to progress or regress based on the company's interests, facilitated by the interaction between the Design and Business Review teams.

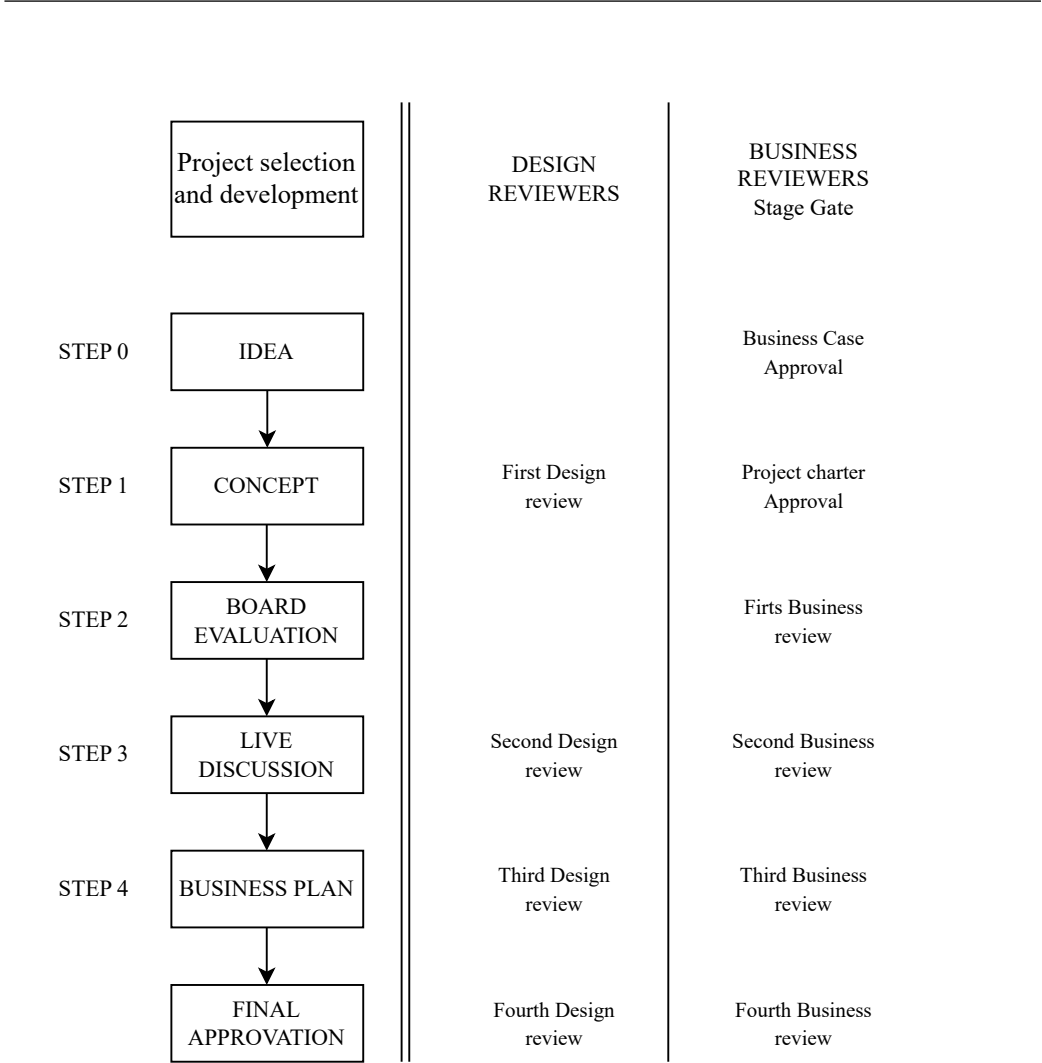


Figure 1.5: Stage-Gate Process in as-is scenario.

This final phase was the most time-consuming, mainly because the company focuses on the biomedical sector. Innovations and updates required a rigorous analysis and review process before they were introduced to the company, whether new products, but also new processes or methodologies. In particular, as can be seen in Figure 1.5, once the idea has passed the

Excel™scoring model, it must undergo four phases of review. These revisions involve changes in both design and business. The review becomes increasingly crucial as the steps progress. In particular, the pivotal transition in this phase occurs between steps 2 and 3, as it shifts from a online interaction to an in-person meeting with related discussions.

This methodology remains valid for a medium-sized company. However, given the exponential growth experienced by the analysed company, the flow of ideas has also increased significantly, making this tool undersized. Hence, there arose a necessity for management to take an additional step by implementing an automated system capable of not only selecting but also cataloguing ideas.

1.2.2.2 Design phase

In the second phase of the challenge, the project shifts its focus to the development of a *co-creation tool* specifically designed for the needs of the company. This tool is not a generic solution, but rather a *taylor-made* platform, purposefully built to enhance collaboration between key internal stakeholders and a range of external partners, including suppliers, customers, and strategic allies. The foundation of this approach is deeply embedded in the principles of *OI*, which posits that valuable and innovative ideas can arise from a blend of internal and external sources, fostering a more holistic innovation process within the company.

To ensure the *tool*'s relevance and effectiveness, a series of targeted interviews were conducted with future users of the platform, both within the organization and externally. These interviews provided a crucial opportunity

to directly gauge the expectations, needs, and specific desires of the platform's key stakeholders. By engaging directly with these stakeholders, the project team was able to gather critical insights, helping shape the direction of the platform's design.

The feedback collected through this consultative process played a pivotal role in forming the initial concept of the *tool*. The resulting outline design incorporated not only the technical requirements but also the desiderata and strategic insights that emerged from these conversations. This iterative process ensured that the co-creation *tool* was aligned with the practical needs of the users and reflected the collaborative, dynamic spirit of Open Innovation.

1.2.2.3 To-be Scenario

Based on the results gathered in the previous chapters, a user journey flow has been developed, outlining the sequence of steps that a user takes within the digital experience. Specifically, following the initial mapping, the following constraints in the development of the tool have emerged:

- i. To avoid bias, *ideas* will be processed and evaluated anonymously.
- ii. A deadline of 11 weeks has been set between the proposal and the in-person discussion step.
- iii. Clearly define the rules for using the *tool*.

At the same time, a preliminary business analysis was conducted to identify the most suitable software development company to digitise the *tool* and integrate it smoothly into the company's intranet infrastructure. The main

objective of this parallel activity was to ensure that the software solution was multi-platform, capable of accommodating the wide range of digital tools used by different users in the organisation's various departments and roles. This approach aimed to improve compatibility and functionality, thereby optimising operational efficiency and user experience during the implementation process.

Specifically, in Figure 1.6 presents the *re-engineered* process, starting from the idea and proposal generation phase up to the final feedback from the designated committee. This makes it possible to appreciate the evaluation and selection process from the point of view of the proposer.

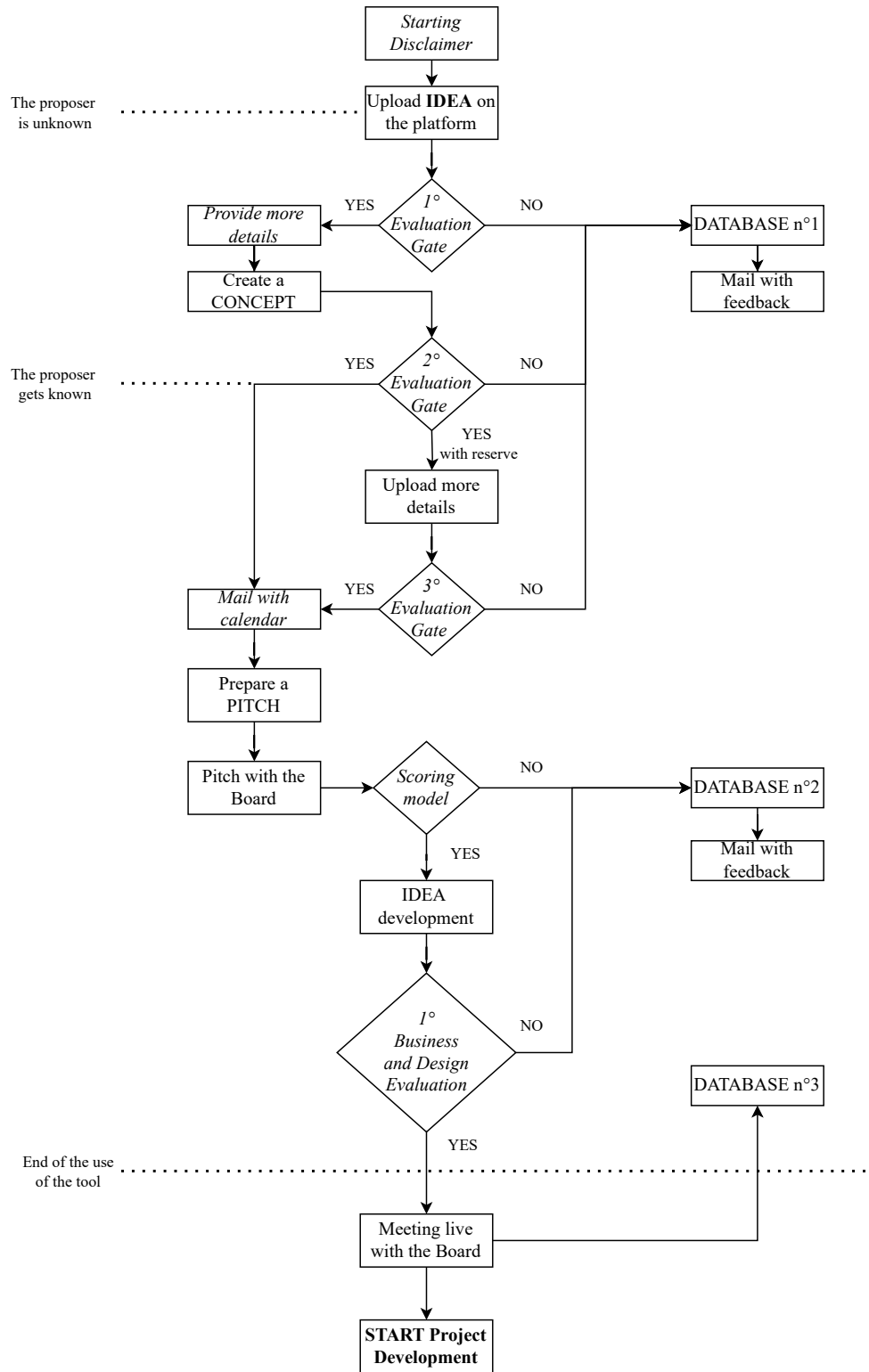


Figure 1.6: User information flux in to-be scenario.

Observing the flow chart in Figure 1.6, it is evident that, even in the to-be scenario, several phase gates remain before the development of the idea begins, as was the case in the as-is phase.

This complexity is a specific desiderata of the company's board of directors because, when it comes to biomedical products, every new idea must be thoroughly analysed from all points of view before starting its development.

Furthermore, the presence of three databases, absent in the as-is phase, allows the ideas received to be archived and categorised. These databases are populated in three different selection phases:

- i. **Database 1.** Contains preliminary ideas, which are initial concepts and suggestions gathered without a specific structure or selection process. These entries represent the starting point for further development and are characterized by a variety of inputs, many of which may still be rough or underdeveloped.
- ii. **Database 2.** Contains more structured ideas that have been analyzed and organized in a more systematic manner. In this database, the ideas have undergone a certain level of development and reflection, and are presented with additional details to facilitate evaluation and comparison. This stage represents an evolution from the initial proposals, with increased attention to coherence and feasibility.
- iii. **Database 3.** Contains ideas that have passed the selection and evaluation process. This database includes only those ideas that have been approved and deemed worthy of further exploration. Each entry in this

archive is well-defined and has met the evaluation criteria, making it ready for subsequent phases of development or implementation.

In addition, following other desiderata that emerged during the interviews, different types of feedback were included that the idea proponent will receive by e-mail during the proposal evaluation phase.

It must be pointed out that what has been described so far is the use from the user's point of view. However, this *tool* envisages two macrocategories of users: the user and the reviewer. For the sake of completeness, the same process observed from the point of view of the Admin is proposed in Figure 1.7, in which it is possible to observe both the steps on the proposer's side, but also the steps faced by the reviewers/evaluators.

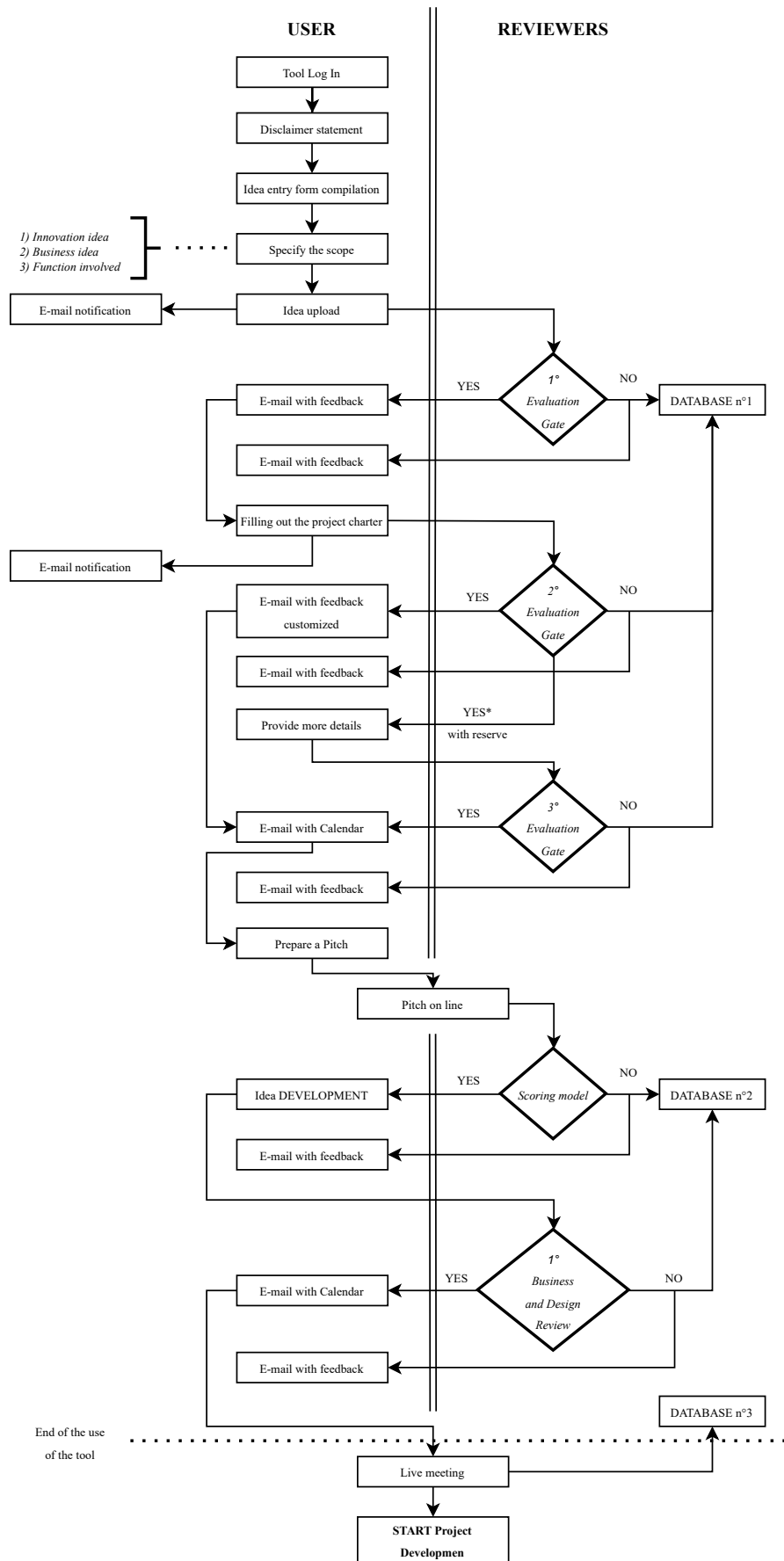


Figure 1.7: Information flux inside the *tool* in to-be scenario.

1.3 Results and discussion

The challenge posed by the company was to develop a process that will be implemented in a *digital tool* capable of identifying and monitoring all innovation opportunities the company may encounter, both internally and externally.

The project was carried out in three phases: initially, in-depth mapping and analysis of the current state (as-is); then, collaborative identification of operational strategies and desires through interviews with key stakeholders in the affected categories (Design). The multidisciplinary approach taken in this project allowed for a comprehensive examination of the problem, analyzing it from different perspectives due to the heterogeneous nature of the working group, which aligns with the principles of Open Innovation.

Then a future scenario (to-be) was presented, detailing the optimal solution that emerged from these previous steps. Throughout the evaluation phase, rigorous critical analysis was maintained in the evaluation process, reflecting the company's focus on the medical sector and ensuring thorough scrutiny before advancing new developments.

The goals of the project include leveraging both internal and external crowdsourcing to tap into the collective intelligence of all the professionals with whom the company deals, fostering a culture of innovation. The research supports crowdsourcing for its ability to generate different ideas and creative solutions, integrating a wide range of perspectives and experiences that traditional top-down approaches might overlook.

Furthermore, the project encourages idea submission from every em-

ployee, promoting inclusivity and empowerment. Generating a range of different ideas not only enhances creativity but also boosts employee morale and engagement, recognizing individual contributions to the innovation process.

Finally, the project focuses on transforming these innovative ideas into tangible business assets by evaluating feasibility, market potential, and strategic alignment. This structured evaluation process ensures that resources are allocated to projects with the highest potential return on investment, driving sustainable business growth and reinforcing the company's competitive edge.

This collaboration facilitated a transformative shift towards an Open Innovation model, with an *Incremental Innovation tool* and leveraging both internal and external innovation potential to establish a lasting corporate asset. Through this first step in the innovation journey, the company's goal is to leverage this new *tool* to be able to generate further innovations in the future in order to generate a *Radical Innovation* process for the entire company.

Appendix

Preliminary Tool Testing

To complete this Chapter, a summary of the *tool* test phase is also given, which took place after the project was completed. This testing phase was crucial to further validate the performance and effectiveness of this new *tool* in real-world scenarios.

Although the testing phase took place outside the scope of the original project, it is crucial to report these results because they confirm the quality of the work performed. The data from this phase not only reinforce the results and conclusions drawn previously, but also offer further insights into the operational success and practical impact of the *tool*.

This section will present a detailed analysis of the results of the test phase, demonstrating how the *tool* performed against the predefined *KPIs*. The results obtained from this extended evaluation serve to affirm the validity of previous design and implementation efforts and to highlight the effectiveness of the *tool* in supporting the company's innovation strategy.

In the context of implementing the new *Open Innovation tool*, the company initiated a testing phase to assess the *tool's* effectiveness. This testing phase was critical for gathering concrete data on key performance indicators (*KPIs*) and understanding the tool's actual impact on idea collection and management.

Table 1.4 provides a detailed summary of the *KPIs* monitored during this testing period. These indicators encompass crucial aspects such as the duration of platform availability, the number of invited and engaged users, and

Table 1.4: KPIs idea-gathering phase.

KPI	Expected	Noted	Δ
Platform opening days	60	67	+11.67%
Total invited users	100	106	+6%
Content sent via newsletter/mail	66	66	—
People trained on the platform	100%	100%	—
Platform visits	—	1916	—
Platform accesses per account	6	18	+200%
Submitter	40	43	+7.5%
Unique visitors	—	102	—
Users involved	—	79	—
People making the first access	80%	96%	+20%
Curious	15%	26%	+73.3%
Actives	50%	49%	−2%
Contributors	10%	8%	−20%
Innovators	10%	14%	+40%
Explorers	15%	14%	−6.67%
Total of ideas proposed	40	97	+142.5%
Total number of ideas per challenge area	10	24.25	+142.5%

metrics related to user activities, including platform access and the volume of ideas submitted.

Additionally, the Table examines user categories defined by the Innovation committee in — *Curious, Active, Contributors, Innovators and Explorers* — to evaluate how each group interacts with the platform (Table 1.5). The percentage values representing these categories refer to a target population of 100 *Expected* users who have access to the platform.

These insights are essential for identifying the *tool*'s strengths and areas for improvement, offering a solid foundation for optimizing the system and

enhancing idea collection and management in future innovation cycles.

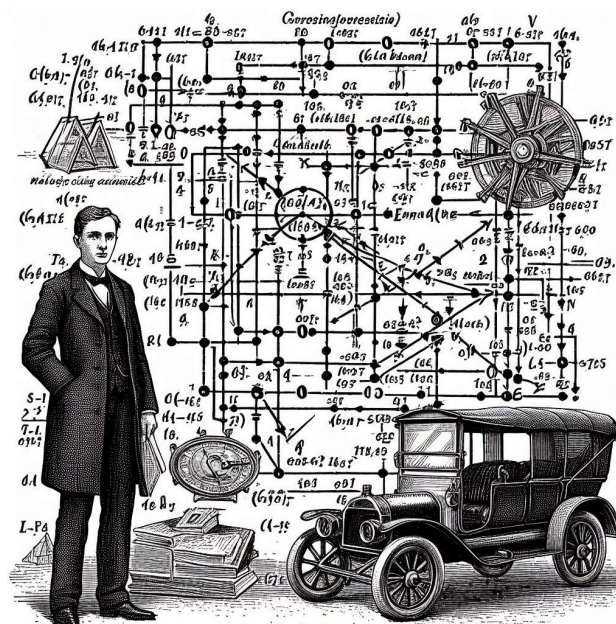
Table 1.5: Users Categories.

Categories	Description
Curious	Users who have logged into the platform at least once
Active	Users who have commented and/or voted on ideas of other proponents at least once
Contributors	Users who posted 1 idea
Innovators	Users who posted 2-3 ideas
Explorators	Users who posted 4 or more ideas

The analysis of the *KPIs* presented in Table 1.4 offers a clear view of the results achieved during the testing phase, facilitating a critical evaluation of the *tool's* effectiveness and its capacity to support the company's innovation processes. Notably, the data indicates that user engagement and the number of submitted ideas significantly exceeded initial expectations. The diverse involvement across user categories demonstrates the *tool's* success in stimulating participation and fostering innovation.

Chapter 2

Process Improvement



Nomenclature and acronyms

The nomenclature and acronyms used in Chapter 2 are presented in Table 2.1.

Table 2.1: Nomenclature and acronyms used in Chapter 2.

Symbol	Description	Unit
<i>DES</i>	Discrete Events Simulation	—
<i>TSP</i>	Travel Salesman Problem	—
<i>SMDP</i>	Simulation Model Development Process	—
<i>AGV</i>	Automated Guided Vehicle	—
<i>SLAP</i>	Storage Location Assignment Problem	—
<i>PD</i>	Picking Distance	<i>m</i>
<i>APD</i>	Average Picking Distance	<i>m</i>
M	Max <i>APD</i>	<i>m</i>
m	Min <i>APD</i>	<i>m</i>
Δ	Difference in <i>APD</i> with different routings	%
<i>RP</i>	Routing Policy	—
<i>RS</i>	Return Simple	—
<i>RAD</i>	Return Advance	—
<i>SSS</i>	S-Shaped Simple	—
<i>SSAD</i>	S-Shaped Advanced	—
x_f	Warehouse Shape Factor	—
x_{fT}	Warehouse Shape Factor Target	—
x_{fR}	Warehouse Shape Factor Real	—

LA	Number of Longitudinal Aisles	—
CA	Number of Cross Aisles	—
a	Width of the warehouse	m
b	Depth of the warehouse	m
α	Width of the storage location	m
β	Depth of the storage location	m
w	Width of the aisles	m
I/O	Input-Output position of picker	—
SCP	Single Central Picking	—
SLP	Single Lateral Picking	—
$OLPSS$	Opposite Lateral Picking, Same Side	—
OCP	Opposite Central Picking	—
OSP	Opposite Side Picking	—
λ	Parameter of the demand distribution	—
i	i^{th} item in the warehouse	—
P	P^{th} storage location in the warehouse	—
n	Number of items to satisfy 80% of demand	—
N	Warehouse storage capacity	—
$R(P)$	Distance to reach the storage location	—
PL	Picking List	—
PDF	Probability Density Function	%
CDF	Cumulative Density Function	%
CF	Number of configurations	—
σ_{APD}	Standard deviation of APD	m

CHAPTER 2. PROCESS IMPROVEMENT

CL	Confidence level	%
CI	Confidence interval	m
t	t -Student critical value	—
$repl$	Numbers of replicates	—
k	k^{th} replicate	—

2.1 Discrete Event Simulation

The term *simulation* refers to a set of techniques for reproducing specific behavior of a real or ideal system, using resources (time and knowledge) to answer questions asked for the structure being studied when real experiments are too costly, both in terms of money and time, or impossible to perform (Kelton et al., 2002).

Discrete Event Simulation (*DES*), is a fundamental methodology within the domains of industrial engineering, logistics, computer science, and numerous other disciplines. It constitutes a modeling technique that aims to represent the dynamic behavior of a system through the sequential simulation of discrete events over time (Trigueiro de Sousa Junior et al., 2019). These events, which can be described as state changes, interactions, or transitions among entities within the system, are treated exclusively and occur only at specific points in time, thus distinguishing *DES* from other forms of continuous simulation.

Within the realms of scientific research and complex systems analysis, *DES* provides a powerful *tool* for exploring the behavior of intricate systems, evaluating design alternatives, optimizing resources, and making informed decisions. By creating models that capture the essential dynamics of the system under study, it becomes possible to conduct simulations to assess the impact of variations in input parameters, decision policies, or operational configurations, enabling users to draw reliable conclusions and implement improvements (Bocelli et al., 2024, Montanari et al., 2022).

2.1.1 Travelling Salesman Problem

The Travelling Salesman Problem (*TSP*) represents a significant combinatorial optimization problem where the objective is to determine the shortest route a salesman must take to visit a set of cities. The primary constraint is that each city must be visited exactly once, and the salesman must return to the starting point. The complexity of the *TSP* arises from the need to find the optimal route among a finite set of cities, considering the distances between them.

The main challenge of the *TSP* lies in efficiently exploring all possible combinations of routes, whose number grows exponentially with the number of cities. This renders an exhaustive solution not feasible, especially for large instances. Therefore, the search for *TSP* solutions is based on search and optimisation algorithms that aim to find approximate solutions or heuristics that approach the optimal path with an acceptable computational cost.

The *TSP* has a wide range of practical applications in fields such as logistics, transportation, tour planning, electronic circuit design, 3D printing, *CNC* machining, and more. Its efficient resolution is crucial for optimizing operations and reducing the costs associated with routing and itinerary planning in real-world contexts.

2.1.2 Overview and theoretical background

Simulation modelling is a powerful methodology for advancing theory and research on complex behaviours and systems and is one of the most widely used operations-research and management science techniques (Law, 2015).

The simulation model was designed according to the Simulation Model Development Process (*SMDP*) approach proposed by Manuj et al., 2009, who have delineated a rigorous framework for the design, implementation, and evaluation of reproducible simulation models.

Figure 2.1 presents an overview of the *SMDP-inspired* investigation approach followed in this study. The procedure consists of four steps, presented below and contextualized in the following sections.

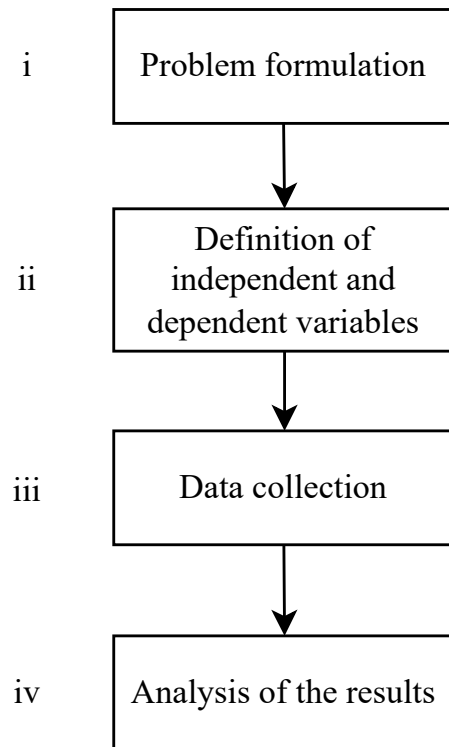


Figure 2.1: The four steps of the SMDP.

- i. **Problem formulation.** The purpose of problem formulation is to define the overall objectives and specific questions to address through simulation. A lack of attention while performing this step can cause the simulation models to fail or produce poor results (Keebler, 2006).

Indeed, simulation models with ambiguous or improperly defined objectives can result in incorrect analysis, time losses, and incorrect inferences, leading to bad or ineffective decisions (Dhebar, 1993). It is true, however, that initially the problem may not be stated precisely or in quantitative terms, and that an iterative procedure may be necessary to reach a precise formulation. To maximize the effectiveness of problem formulation and ensure that all the relevant aspects of the issue are being captured, it is usually a good practice to involve individuals who have previously dealt with the same, or similar, situations. When the problem is clearly stated, it is possible to properly define the performance indicators of interest, the scope of the model, the time frames, as well as the resources required for the analysis. In the case under examination, the simulation model was designed with the purpose of reproducing a manual picking process in a traditional warehouse and evaluating its performance in terms of the average picking distance (*APD*) travelled by the picker to fulfil orders with different picking list sizes.

- ii. **Definition of independent and dependent variables.** Independent variables, used as model inputs, represent the characteristics and the parameters of the system, while the dependent variables reflect its performance, i.e., *APD*, estimated through simulation. The values of the independent variables are modified during the simulation campaign, to evaluate their impact on the dependent variables and address the problem formulated in step 1. Obviously, the outcomes of a simulation

campaign depend on what has been included in the model formulation. Therefore, the selection of the independent and dependent variables must be based on the objectives of the research and the specific questions that emerged during the problem formulation. In general, all the factors that have the potential to influence the outcomes of the system should be included in the model (Towill and Disney, 2008; Potter and Disney, 2006). The independent and dependent variables included in this study are detailed in the following sections.

- iii. **Data collection.** Collecting data can be challenging, as it may not be immediately available in the required format or the appropriate level of detail. It is essential, therefore, to properly define the data requirements, according to the specific model parameters, the system's layout, the operating procedures, and the probability distributions of the variables of interest. In this study, the data necessary for the analysis of the results and for the evaluation of the different picking strategies will be generated and collected in the appropriate form during the simulation campaign.
- iv. **Analysis of the results.** Finally, the results obtained must be analysed to derive the relevant insights. Various techniques can be used to this end, e.g., visual examination of the graphical results, analysis of the mean value and the lower and upper limits, or even analyses carried out through the use of advanced techniques. In this study, visual inspection of the graphical results, coupled with data elaboration, was considered to be the appropriate technique for the analysis of the

simulation outcomes. A visual inspection was deemed appropriate for this study because, as will be discussed in detail below, only a subset of the values generated was analysed.

2.2 DeS: Case Study

In most warehouses, the order picking process is an activity that strongly impacts performance in terms of operating costs, time required, and labor. As a result, any delay in this operation, generates delays on the entire supply chain (Amorim-Lopes et al., 2021). In the last few years, e-commerce has increased exponentially. As a result, warehouses were faced with having to manage a wider and more varied range of products to meet customer needs. This created strong pressure to improve warehouse efficiency in order to handle an increasing volume of orders, reduce lead times, minimize errors, and optimize the entire logistics process. Adoption of advanced technologies and optimization of warehouse operations have become crucial strategies to remain competitive in this rapidly changing industry. Increasing the performance of warehouses thus turns out to be not only a necessary activity but also a challenging topic for many researchers (Hall, 1993; Jarvis and McDowell, 1991; C. G. Petersen, 1999; C. G. Petersen and Aase, 2004).

Order picking, is an activity that basically consists of an entry into the warehouse, performed manually by an operator (Bertolini et al., 2023) rather than an Automated Guided Vehicle, AGV (Teck et al., 2023), perform a path in order to collect all the items on the picking list and exit the warehouse. Several studies can be found in literature concerning the analysis and implementation of the performance of traditional warehouses as described in the work of Bottani et al., 2018, rather than warehouses with non-conventional layouts, e.g. a fishbone layout (Esmero et al., 2021). Performance enhancement can be reached either through hardware implementations, i.e., working

on the geometry of the warehouse, rather than software i.e., operating on the warehouse management policies themselves (Montanari et al., 2022), or different market demand (Bocelli et al., 2024).

In other studies, the authors focused their analysis on the Storage Location Assignment Problem (*SLAP*): which can be grouped into three main categories: dedicated storage, shared storage and class-based storage (Brynzér and Johansson, 1996). Using dedicated storage, the position of each items is according to its rotation index (Bottani et al., 2012; Millstein et al., 2022), i.e. by classifying products and placing those most in demand on the market in positions to minimise the distance travelled in the picking phase; on the other hand, other authors analyse performance efficiency methods involving scattered storage method (M. Liu and Poh, 2023). In this last case, warehouse efficiency is increased not during the picking phase, but during the replenishment phase. It is also possible to use a class-based allocation, whereby the warehouse is sectorised according to specific characteristics common to several items, e.g. through a volume based location policy (Berglund and Batta, 2012).

More studies analyse the impact of different routing policies within the warehouse on the path travelled by the picker (Montanari et al., 2021). Other studies have also evaluated the possibility of applying the batch-picking strategy, i.e., grouping several small orders into a single mission, to be followed by a sorting operation once the picking mission has been executed. In this regard, it has been shown that picking times can be reduced by 17–22% by applying this management method (C. G. Petersen, 2009). Various approaches are also applicable to quantify the improvements made with the studies

described above: mathematical models, decision support systems, heuristic algorithm, multidimensional data mining technique, simulation technique (Yener and Yazgan, 2019).

In this chapter, *TSP* using the *DES* method will be explored and analysed by applying it to an optimisation problem in industrial logistics, specifically by minimising the distance travelled by a picker during the order processing within a traditional warehouse (Bocelli et al., 2024; Montanari et al., 2022). This work aims to contribute to the literature in two main ways. First, it evaluates the performance of the order picking process based on various software and hardware inputs, with a focus on routing policies and product allocation according to market demand, which can fluctuate. The demand modeling allows for the analysis of scenarios ranging from random storage to dedicated assignments, assessing the impact of external factors on warehouse performance. Second, the study introduces a simulation-based design *tool* that considers various picking factors, enabling the simulation of a wide range of practical scenarios.

2.2.1 Problem formulation

The simulation model was designed according to the *SMDP* approach proposed by Manuj et al., 2009. Minimisation of the *APD* through the appropriate tuning of the system parameters was identified as the objective of this study, because it can significantly reduce the time required to complete a picking task and, consequently, enhance the efficiency and productivity of the entire warehouse management process. However, the analysis did not

focus on *APD* minimisation only. Indeed, an additional critical analysis was carried out to highlight that, in some contexts, it is preferable to choose a configuration that is not fully optimized in terms of *APD*, but can generate operational benefits, e.g. simplification of the picking routes and/or the warehouse layout itself.

2.2.2 Definition of independent and dependent variables

This section will define the dependent and independent variables that are used in the simulation *tool* presented in this chapter. For developing the simulation model, and generating the dataset required for the analysis, the following assumptions were made:

- i. Each location may contain one storage unit only.
- ii. Each storage location contains a different product handled in the warehouse. This implicitly means that the number of products equals the storage capacity (N).
- iii. The picker's route around the shelves is Manhattan metric.
- iv. A manual order picking process is performed.

2.2.2.1 Independent variables

The input variables used embodied in the model are presented below.

2.2.2.1.1 Warehouse layout

Defining the warehouse layout means setting the elements listed below.

- i. Storage capacity (N). N is set as an input parameter for defining the storage capacity of the warehouse, where each product has one ground-level storage location. By storage location, it is meant the generic spatial unit in a warehouse, in which something is stored, while a picking location is a storage location in which an item to be picked is located (Roodbergen and de Koster, 2001).
- ii. Number of cross aisles (CA). The number of CAs , in addition to the front and back aisles, defines the number of blocks into which the warehouse can be divided, as shown in Figure 2.16, presented in Section 2.2.3.1. Whenever cross aisles are present, the warehouse is divided into a number of blocks equal to the number of cross aisles plus one (Roodbergen and de Koster, 2001).
- iii. Width of the aisles (w). This parameter allows for increasing the types of warehouses to be simulated, e.g., from an aisle allowing for the passage of a picker only, to ones that allow the passage of a traditional forklift or a trilateral one (Suppini et al., 2023).
- iv. Size (width, α , and depth, β) of the storage location. The usage of α and β as problem variables allows for reproducing storage locations of various size, ranging from a storage area for standard *EPAL* pallets or *ISO* containers, depending on the simulation requirements. This flexibility, achieved by adjusting the α and β values, makes it possible to move from the simulation of small objects to the modelling of larger entities, expanding the adaptability of the model.

- v. Shape factor (x_f). The shape factor x_f reflects the geometric characteristic of the building in which the warehouse is located. The shape factor defines the ratio between the width (a) and the depth (b) of the building, as shown in Equation 2.1.

$$x_f = \frac{a}{b} \quad (2.1)$$

Values of x_f greater than 1 refer to a warehouse that develops mainly horizontally (Figure 2.2); values of x_f close to 1 denote a warehouse with a shape similar to a square (Figure 2.3); finally, x_f values smaller than 1 refer to warehouses with a narrow and elongated shape (Figure 2.4).

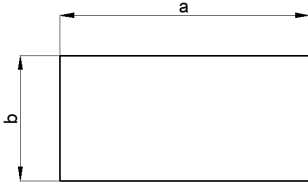


Figure 2.2: $x_f > 1$.

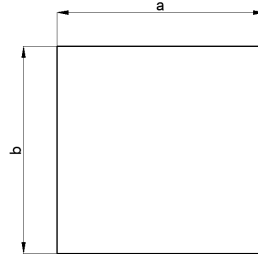


Figure 2.3: $x_f = 1$.

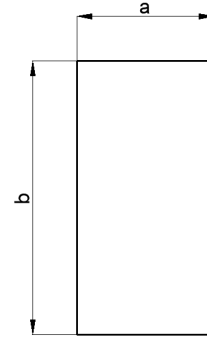


Figure 2.4: $x_f < 1$.

2.2.2.1.2 I/O Position

By setting different *I/O* positions, various paths within the warehouse can be generated. Five different *I/O* configurations were considered, differentiated by the position of the entry and exit points.

- i. Single Central Picking (*SCP*): single central entry and exit point (Figure 2.5).

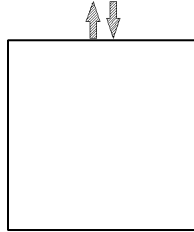


Figure 2.5: Single Central Picking configuration.

- ii. Single Lateral Picking (*SLP*): single lateral entry and exit point (Figure 2.6).

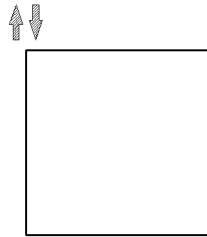


Figure 2.6: Single Lateral Picking configuration.

- iii. Opposite Lateral Picking Same Side (*OLPSS*): lateral entry and exit points located on the same side of the warehouse, with the entry at the beginning and the exit at the end of the aisle (Figure 2.7).

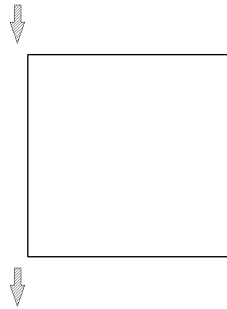


Figure 2.7: Opposite Lateral Picking Same Side configuration.

- iv. Opposite Central Picking (*OCP*): central entry and exit points, with the entry point at the beginning and the exit at the end of the aisle (Figure 2.8).

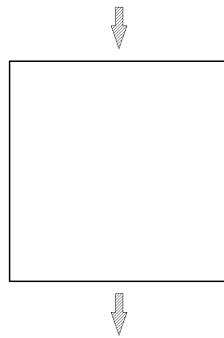


Figure 2.8: Opposite Central Picking configuration.

- v. Opposite Side Picking (*OSP*): lateral entry and exit points on opposite sides of the warehouse (Figure 2.9).

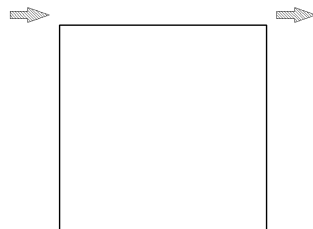


Figure 2.9: Opposite Side Picking configuration.

2.2.2.1.3 Routing Policy

The *RP* reflects the logic followed by the picker for moving in the warehouse as efficiently as possible during the picking process. Four different *RP* are evaluated and listed below:

- i. Return Simple (*RS*): the picker enters and exits the aisles from the same side, collecting the items first from one side of the aisle in the entry phase, and picking from the opposite side in the exit phase. Aisles without items to be retrieved are not visited (Figure 2.10).
- ii. Return Advanced (*RAD*): this policy is similar to *RS*, except that in this case the picker can also move through the cross aisles (Figure 2.11).

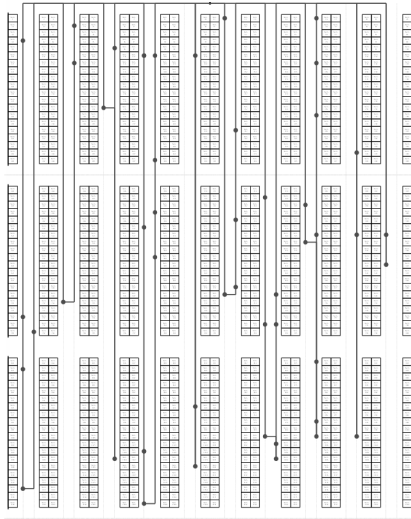


Figure 2.10: Return Simple policy.

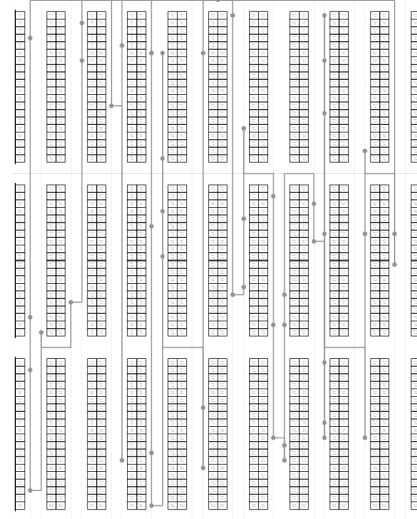


Figure 2.11: Return Advanced policy.

- iii. S-Shaped Simple (*SSS*): no cross-aisles are used during picking operations, so the picker has to travel the whole aisle each time he/she

iv. S-Shaped Advanced (*SSAD*): the policy is the same as that above, apart from the fact that the cross-aisles can be utilized during picking operations (Figure 2.13).

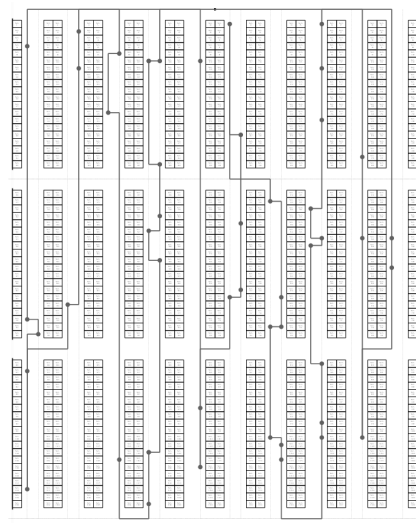


Figure 2.13: S-Shaped Advanced policy.

Varying the demand distribution allows for simulating different market types, ranging, in particular, from a *uniformly distributed market*, in which each reference has the same probability of being requested by the customer, to a *fully heterogeneous market*, including both high-rotating and low-rotating items. To capture this behaviour, an appropriate probability density function (*PDF*) was defined and implemented in the simulation model as shown in Equation 2.2.

$$PDF(i) = \frac{e^{-\lambda i} (e^\lambda - 1)}{1 - e^{-\lambda N}} \quad (2.2)$$

where:

- i. i : any product in the warehouse ($1 \leq i \leq N$).
- ii. N : warehouse storage capacity.
- iii. λ : is the parameter that allows for depicting different market scenarios.
When $\lambda \rightarrow 0$, all products are equally likely to be requested by the market, meaning that each product has the same rotation index. On the other hand, when λ increases, the demand (i.e., the market) becomes more concentrated on specific products, leading to different rotation indices for different products.
- iv. $PDF(i)$: is the probability that product i will appear in the order list based on the market demand.

In this study, seven λ values were evaluated, which move from a uniformly distributed market $PDF_{\lambda \sim 0}$, up to a strongly heterogeneous market $PDF_{\lambda=0.05}$. The Cumulative Density Function (CDF) for product i is shown in Equation 2.3.

$$CDF_\lambda(i) = \sum_{x=1}^i PDF_\lambda(x) \quad (2.3)$$

Figure 2.14 presents the trend of PDF and CDF for a warehouse with $N = 1,200$ items. Each curve corresponds to one of the seven λ values analysed. Table 2.2 also shows the number of picking positions (n) that

must be visited for each λ value, to meet at least 80% of market demand (CDF).

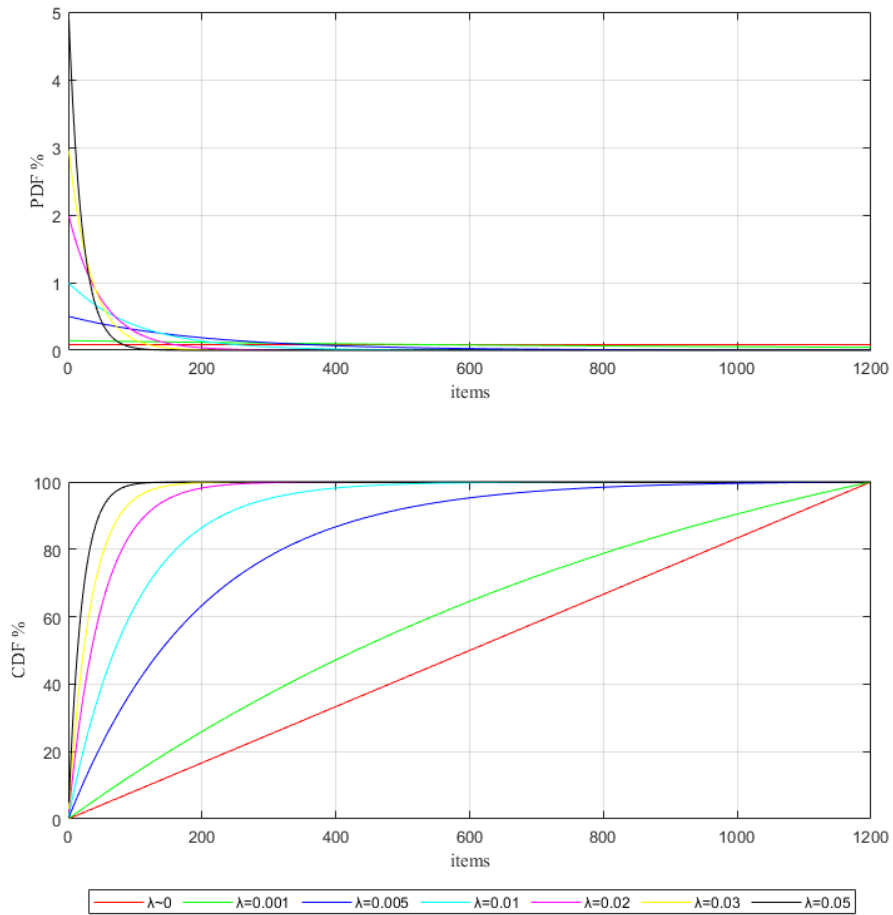


Figure 2.14: Trends of PDF and CDF for different λ values and $N = 1,200$.

Table 2.2: Items required to achieve 80% probability of meeting market demands (CDF), with $N = 1,200$.

λ	n	$n\%$
0	960	80%
0.001	819	68%
0.005	320	27%
0.01	161	13%
0.02	81	7%
0.03	54	5%
0.05	32	3%

2.2.2.1.5 Number of items in the picking list

In developing the simulator, four picking lists (PLs) of different lengths were taken into account as representative of typical sizes of order lists to be completed in a single picking task (H. Liu et al., 2022; C. Petersen, 1997); in detail, PLs of 10, 20, 30 and 50 items were simulated. Short PLs were not merged to generate larger lists (Montanari et al., 2022). To generate the picking lists, a random number was extracted from a uniform distribution in the range $(0; 1]$ for each item to be collected; hence, the inverse function of eq. 3 was applied as the λ parameter varied. With reference to the CDF curves in Figure 2.14, it should be noted that the inverse function shows a transition from a continuous domain to a discrete codomain (Equation 2.4).

$$CDF^{-1} : \mathbb{R}^+ \rightarrow \mathbb{N} \quad (2.4)$$

2.2.2.2 Dependent variable

In the current study, the picking distance (PD) was taken as the only dependent variable. In particular, for each configuration of the warehouse (CF), several simulation replicates were performed. Each PD_k returned by the model is a function (f) of the geometric *tool* (g) and the picking simulator (h), as shown in Equation 2.5.

$$PD_k = f[g(x_f, CA, I/O, N, \alpha, \beta, w), h(PL, RP, \lambda)] \quad (2.5)$$

The final value of APD is obtained by averaging the results of the simulations performed for each CF , to which several random picking lists were matched.

2.2.3 Simulation model

A schematic representation of the *simulation tool* developed is presented in Figure 2.15. As can be observed, the model consists of two main parts that communicate with each other during the simulation process.

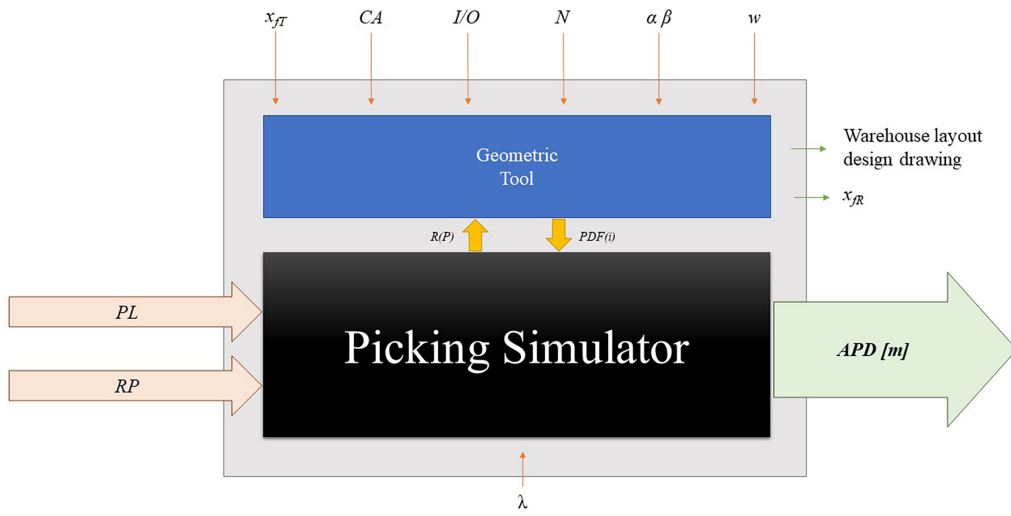


Figure 2.15: Scheme of the simulation model.

The steps followed by the *simulation tool* (and the corresponding outcomes) are as follows:

- i. Geometric representation of the warehouse.
- ii. Ranking of the storage location based on the calculation of their distances to I/O positions.
- iii. Definition of the product allocation according to the demand behaviour and the ranking of the storage location.

- iv. Simulation of the order processing, under different routing policies, with APD as output.

The product allocation and the ranking of the picking positions are recalculated at each simulation replicate, as they depend on both the geometry of the warehouse and the heterogeneity of market demand.

2.2.3.1 Geometric representation

The first part of the model, in blue, represents the *geometric tool*, programmed to generate a virtual model of the system, and capable of defining the storage locations of the warehouse. For reproducing the system's geometry, the *tool* uses the following input data:

- i. Target warehouse shape factor x_{fT} .
- ii. Number of cross aisles (CA).
- iii. Position of the picker's entrance and exit from the warehouse (I/O).
- iv. Warehouse storage capacity (N);
- v. Width (α) and depth (β) of the storage location.
- vi. Width of the aisles (w).

After generating the virtual model of the entire warehouse, the geometric tool calculates its size, real shape factor, and layout.

Regarding the real shape factor (x_{fR}), it is important to note that the system is obviously constrained, as integer numbers only can be used for

some parameters of the warehouse. For example, it is not possible to consider fractions of allocations or corridors. Hence, a *target* x_{fT} is initially set, reflecting the expected ratio between the width and depth of the warehouse. In generating the warehouse layout, the simulation model takes into account x_{fT} , but at the same time determines x_{fR} based on the warehouse parameters: the x_{fR} will be the one that most closely approximates x_{fT} among all possible x_f that satisfy the integer constraints (Equation 2.6). Small dissimilarities can obviously occur; hence, x_{fR} is always returned by the model for benchmarking purposes (Bottani et al., 2019a).

$$x_{fR} = f(N, CA, w, \alpha, \beta, x_{fT}) \quad (2.6)$$

In this study, 10 different x_{fR} are evaluated (Table 2.3); these values were generated by setting $N = 1,200$, $CA = 3$, $w = 3m$, $\alpha = 1m$ and $\beta = 1.25m$.

Table 2.3: Shape factors evaluated in the study.

x_{fR}	LA	a [m]	b [m]
0.14	4	22	162
0.21	5	27.5	132
0.29	6	33	112
0.51	8	44	87
0.76	10	55	72
1.06	12	66	62
1.59	15	82.5	52
2.62	20	110	42
3.57	24	132	37
3.82	25	137.5	36

For the sake of clarity, Figure 2.16 shows an example of a warehouse

layout, in which α and β are set at 1 m and 1.2 m, respectively, w is set at 2.5 m, and x_{fT} is set at 1.5.

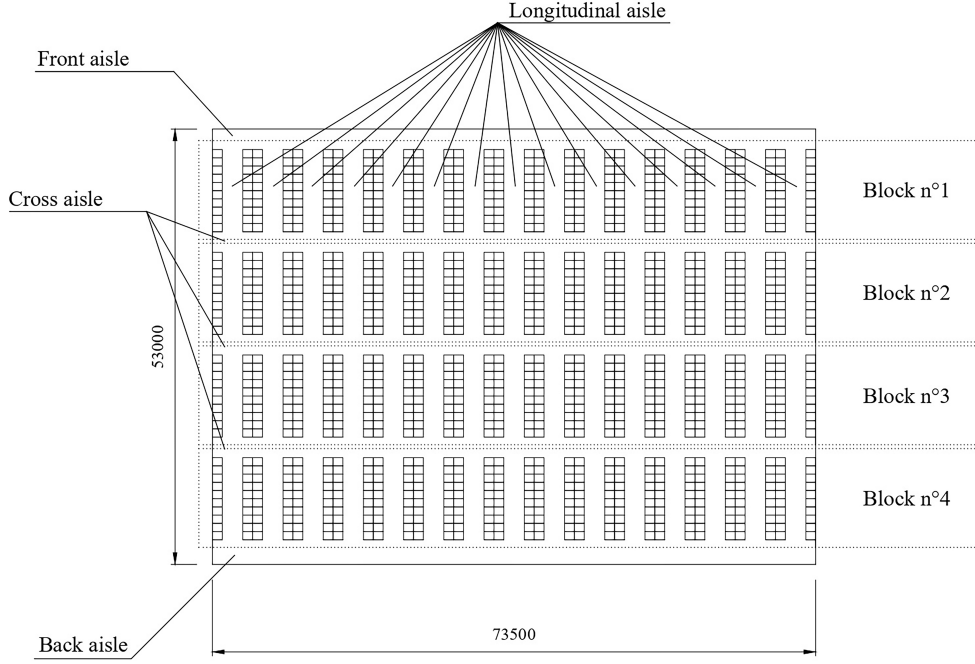


Figure 2.16: Example of layout design of the warehouse with $N = 1,200$, $CA = 3$, $I/O = SCP$. Quotes in mm.

Based on these input values, the geometric tool returns:

- i. The *real* warehouse shape factor, $x_{fR} = 1.38$
- ii. The warehouse width, $a = 73.5m$
- iii. The warehouse depth, $b = 53m$

2.2.3.2 Ranking of the storage locations

Each product (i) considered in this study has its own $PDF(i)$, therefore the simulator, based on the number of LA and on the I/O positions, performs a

ranking $R(P)$ of each storage location (P), according to its distance from the entry ($\overline{IP}$) and exit ($\overline{PO}$) points (Equation 2.7). The optimal allocation will be the one that minimises the distance travelled by the picker on a picking task.

$$R(P) = \overline{IP} + \overline{PO} \quad (2.7)$$

A graphical representation of Equation 2.7 is shown in Figure 2.17 for an *OSP I/O* configuration.

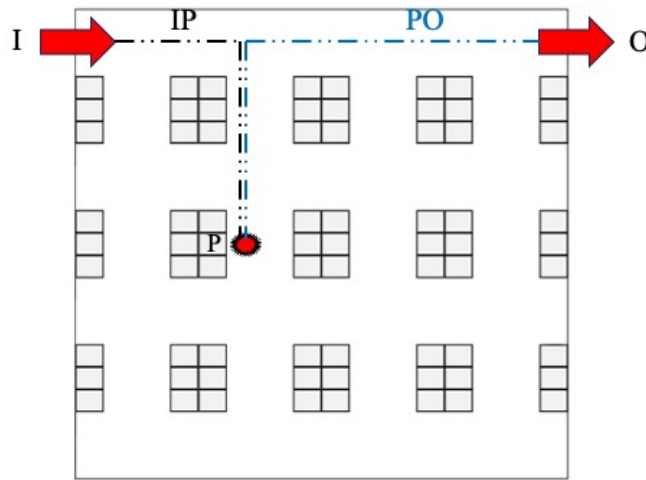


Figure 2.17: Graphical representation of $R(P)$.

It should be noted that the $R(P)$ value does not reflect the Euclidean distance but must account for the presence of geometric constraints, i.e., the presence of shelves and the position of the cross aisles.

2.2.3.3 Definition of the product allocation

The second part of the simulation *tool*, in black in Figure 2.15, is the picking simulator and receives as input the following data:

- i. Picking list (PL).
- ii. Routing policy (RP).
- iii. Coefficient related to demand distribution (λ).

This part of the simulator communicates with the first section, described above, as any variation in the market demand obviously influences the allocation of items within the warehouse. This allows for generating an output, in terms of APD , that takes into consideration both hardware and software constraints of the warehouse under examination. In particular, the simulator matches the items in decreasing order of the $PDF(i)$ with the storage location (from the most favourable location to the worst one), based on the previously calculated value of $R(P)$, as shown in Equations 2.8; 2.9; 2.10.

$$\tilde{R}(P) = R(P), \quad 1 \leq P \leq N \mid R(P+1) > R(P) \quad (2.8)$$

$$P\tilde{D}F_{\lambda}(i) = PDF_{\lambda}(i), \quad 1 \leq i \leq N \mid PDF_{\lambda}(i+1) < PDF_{\lambda}(i) \quad (2.9)$$

$$\tilde{R}(P) \rightarrow P\tilde{D}F_{\lambda}(i) \mid P = i \quad (2.10)$$

Depending on the hardware configuration set, the application of the above formulae enables the complete mapping of all storage locations. Accordingly, the item with the highest probability of being requested by the market will be placed in the most favourable position, while the item with the lowest

probability of being requested will be placed in the most unfavourable position. An illustrative example is provided in Figure 2.18, showing a colormap for a traditional warehouse adopting the *SCP* configuration. Notably, each storage location is *color-coded*, accordingly with its $R(P)$ previously defined, ranging from green (optimal ones) to red (less favorable ones).

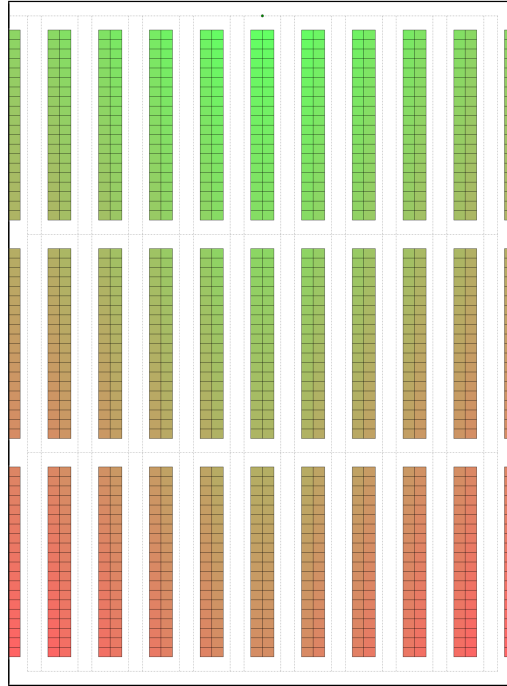


Figure 2.18: Graphical representation of $R(P)$ for a *SCP* configuration.

2.2.3.4 Simulation of the order processing

In this analysis, a traditional warehouse layout with double-sided racking was modelled, with $N = 1,200$ storage locations. These are characterized by $\alpha = 1m$ and $\beta = 1.25m$, while *CA* and *LA* have $w = 3m$. In addition to the front and rear aisles, there are also two *CA* in the warehouse, resulting in a *3-block layout* (Figure 2.19). Considering these assumptions, a full factorial

plan was used to simulate all the possible combinations of the independent variables, resulting in a total of 5,600 simulated configurations, as reported in Equation 2.11.

$$CF = n^{\circ}RP \cdot n^{\circ}x_f \cdot n^{\circ}I/O \cdot n^{\circ}PL \cdot n^{\circ}PDF = 5,600 \quad (2.11)$$

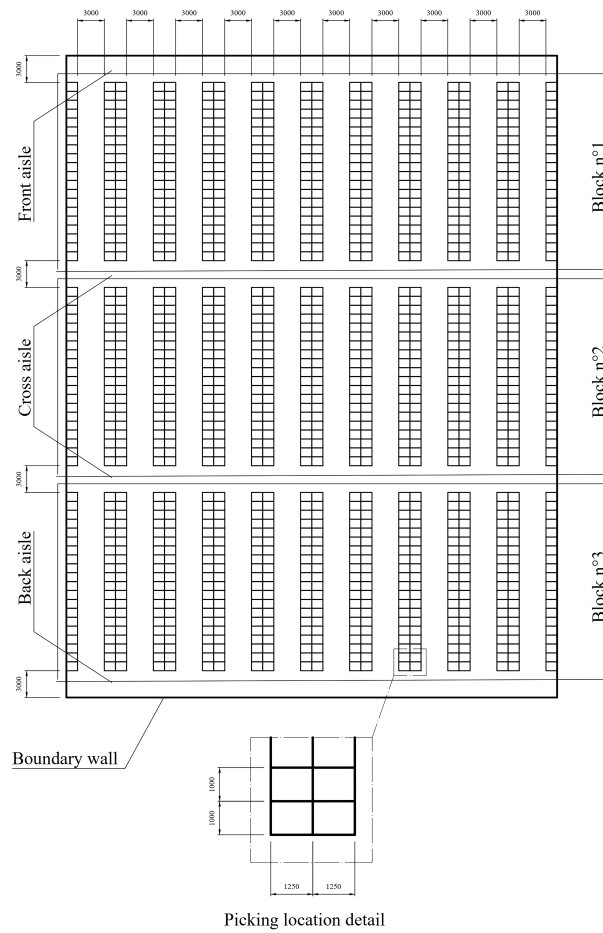


Figure 2.19: 3-block warehouse layout. *Quotes in mm.*

2.2.4 Model validation

2.2.4.1 Statistical analysis

To provide statistical significance to the outcomes of Equation 2.5, a suitable number of replicates ($repl$) to be adopted was determined (Equation 2.12):

$$APD = \frac{\sum_{k=1}^{repl} PD_k}{repl} \quad (2.12)$$

In this analysis, assuming a normal distribution of the values, the confidence interval (CI) will be defined by the *t-Student* distribution. Equation 2.13 is used to define the CI , adopting a *t-value* according to a 95% confidence level (CL).

$$CI = \frac{\sigma_{APD}}{\sqrt{repl}} \cdot t_{\left(\frac{1-CL}{2}, repl-1\right)} \quad (2.13)$$

For testing purpose, this procedure was applied to a specific configuration of the database under investigation, whose characteristics are shown in Table 2.4.

Table 2.4: Detail of the configuration chosen for analysis.

N	$\alpha[m]$	$\beta[m]$	LA	CA	$a[m]$	$b[m]$	I/O	$w[m]$	PL	λ	RP
1,200	1	1.25	4	2	22	162	SCP	3	10	~ 0	RS

In the present case, a configuration with the lowest values of both PL and λ was chosen to validate the analysis. Thus, equation (2.13) was applied to the configuration shown in Table 2.4 with different levels of replicates (ranging from 20 to 15,000). Figure 2.20 illustrates the varying values of the

resulting confidence intervals ($CI\%$) as the number of replicates increases.

The simulation model was developed by implementing VBA code within Excel™ software, run on a machine with an Intel® Core™ i9-10885H CPU @2.40 GHz processor and 64 GB of RAM. The computational time for each configuration was 6.63×10^{-9} seconds.

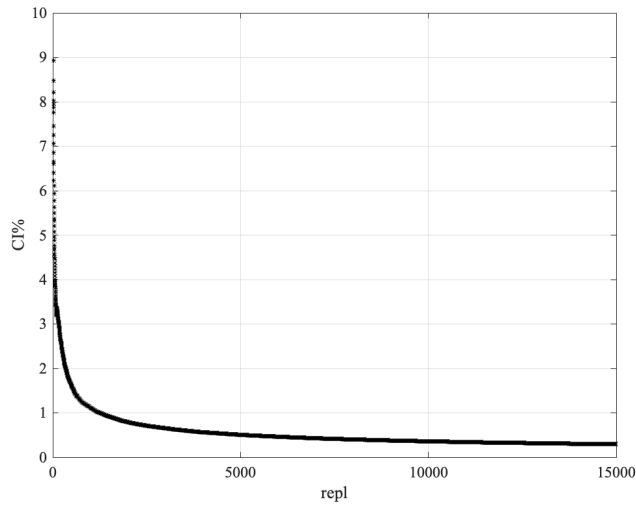


Figure 2.20: $CI\%$ with different numbers of replications.

As can be seen from Figure 2.20, with a number of replicates equal to 10,000 and a CL of 95%, the $CI\%$ turns out to be 0.36%, corresponding to an APD value equal to $856.31m \pm 3.071m$; no tangible benefits emerge if further increasing the number of replicates. On the basis of this result, a number of 10,000 replicates was judged adequate for the scope of the paper.

The $CI\%$ values of the whole dataset plotted against their APD are shown for completeness in Figure 2.21.

As can be seen from the graph in Figure 2.21, by performing 10,000 simulations for each configuration, the confidence interval for a 95% confidence

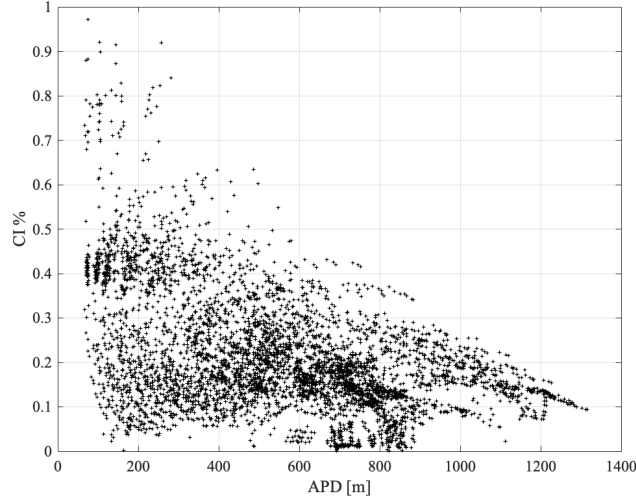


Figure 2.21: $CI\%$ plot with a 95% of CL .

level of the values is always less than 1% of the APD .

2.2.4.2 Model test

This section provides a validation of the model outlined above. This is shown below for a simplified warehouse configuration, whose input data are listed in Table 2.5.

Table 2.5: Input data for model validation.

N	$\alpha[m]$	$\beta[m]$	LA	CA	$a[m]$	$b[m]$	I/O	$w[m]$	PL	λ
192	1	1.25	4	2	22	36	SLP	3	10	~ 0

A random PL of 10 items was generated and the four different routing policies were applied to pick up these items from the warehouse. Each RP generates a different path, these picking paths (PD) are shown in Figure 2.22 and in Figure 2.23 for RS and RAD policies; and in Figure 2.24 and in Figure in Figure 2.25 for SSS and $SSAD$ policies respectively.

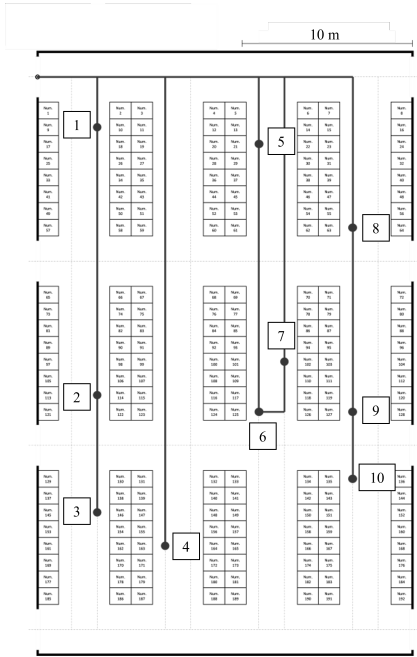


Figure 2.22: Path with *RS* policy.

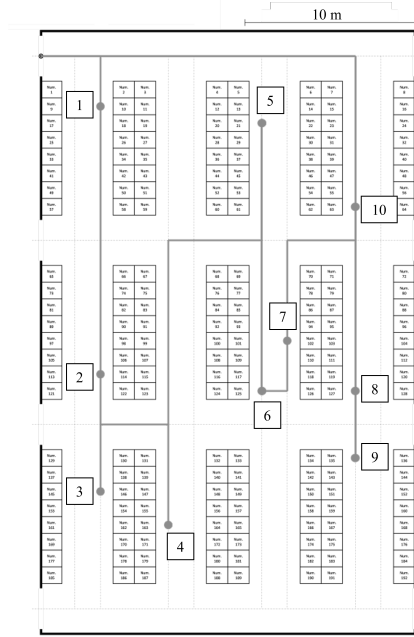


Figure 2.23: Path with *RAD* policy.

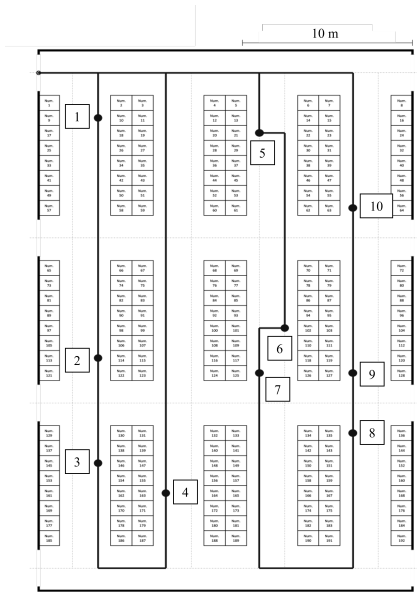


Figure 2.24: Path with *SSS* policy.

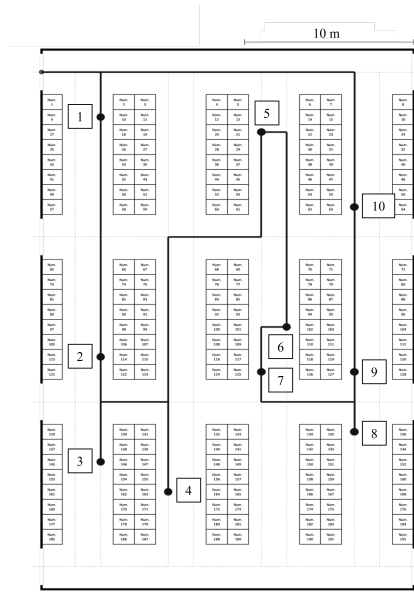


Figure 2.25: Path with *SSAD* policy.

Table 2.6 shows the PD values with the 4 different policies described above.

Table 2.6: Picking distance values.

PD_{RS} [m]	PD_{RAD} [m]	PD_{SSS} [m]	PD_{SSAD} [m]
233	201	172	144

2.2.5 Dataset analysis

2.2.5.1 Investigation boundaries

In analysing the results, particular attention was paid to a part of the dataset, to investigate:

- i. Two I/O configurations: SCP and SLP .
- ii. Three values of LA : 8 ($x_{fR} = 0.51$); 12 ($x_{fR} = 1.06$); 15 ($x_{fR} = 1.59$).

The rationale for limiting the analysis to these aspects is that of using hardware parameters (LA and I/O values) typically observed in real scenarios, which increases the likelihood of investigating warehouse configurations suitable for practical implementation.

The remaining input parameters were instead fully evaluated, as reported in Table 2.7. By including all λ values, several possible demand scenarios were analysed, from a uniformly distributed to a strongly sectorised demand.

By combining the set of parameters in Table 2.7, the total number of configurations analysed turns out to be as follows Equations 2.14-2.15 by replacing the numerical values to achieve the number of 672 configurations.

$$CF = n^\circ\lambda \cdot n^\circ I/O \cdot n^\circ RP \cdot n^\circ LA \cdot n^\circ PL \quad (2.14)$$

$$CF = 7 \cdot 2 \cdot 4 \cdot 3 \cdot 4 = 672 \quad (2.15)$$

Table 2.7: Variable values assumed in the analysis to generate configurations.

λ	I/O	RP	LA	PL
~ 0	SCP	RS	8	10
0.001	SLP	RAD	12	20
0.005		SSS	15	30
0.01		$SSAD$		50
0.02				
0.03				
0.05				

2.2.5.2 SCP and SLP configurations

Figure 2.26-2.27-2.28 and Figure 2.29-2.30-2.31 refer to the SCP and SLP I/O configurations, respectively. In each Figure, corresponding to a single LA value, there are four plots, corresponding to the 4 PLs . In each graph, APD is represented as a function of the λ value. In addition, four curves in each graph depict the four RP evaluated in this study (i.e., RS , RAD , SSS , $SSAD$). From an initial analysis, it emerges that when applying the SSS policy, APD is weakly influenced by variations in the λ parameter, except in the case of very small PLs (10 items); in that case, a slight dependence on λ can be observed, albeit lower than the remaining policies. A justification for this behaviour is to be found in the functioning of the SSS logic itself, in which the picker, once entering an aisle to pick an item, is forced to travel it

entirely and exit on the opposite side. Consequently, having a *PL* with a wide number of items increases the probability of covering the entire warehouse during picking travel. Even if λ increases, i.e., when considering *high-rotating* and *low-rotating* articles, no significant improvements in the performance can be observed. Indeed, it is true that the items with the highest demand will be placed close to the *I/O* point, but this also means that they will be placed as close as possible to the front aisles, and consequently, they will fall in different *LAs*; hence, again when using the *SSS* policy, no remarkable reduction in the *APD* can be observed. These outcomes reinforce the consideration that, in general, the *S-shaped* routing policy is not particularly effective (C. G. Petersen, 1999); this is also true in contexts in which the demand patterns can vary.

An interesting result also arises from these plots shown in the following pages: apart from the *SSS* policy analysed above, it can be observed that for $\lambda \geq 0.01$, the *RS*, *RAD*, and *SSAD* policies show similar outcomes in terms of *APD*. This outcome complements the available knowledge by highlighting that in some contexts (although somehow difficult to observe in real scenarios as market demand is highly heterogeneous), these policies could be considered interchangeable, and the usage of any of them would not affect the performance of the picking process. Ultimately, this allows good flexibility in the choice of the *RP*, which can be set according to the specific needs and constraints of the application context.

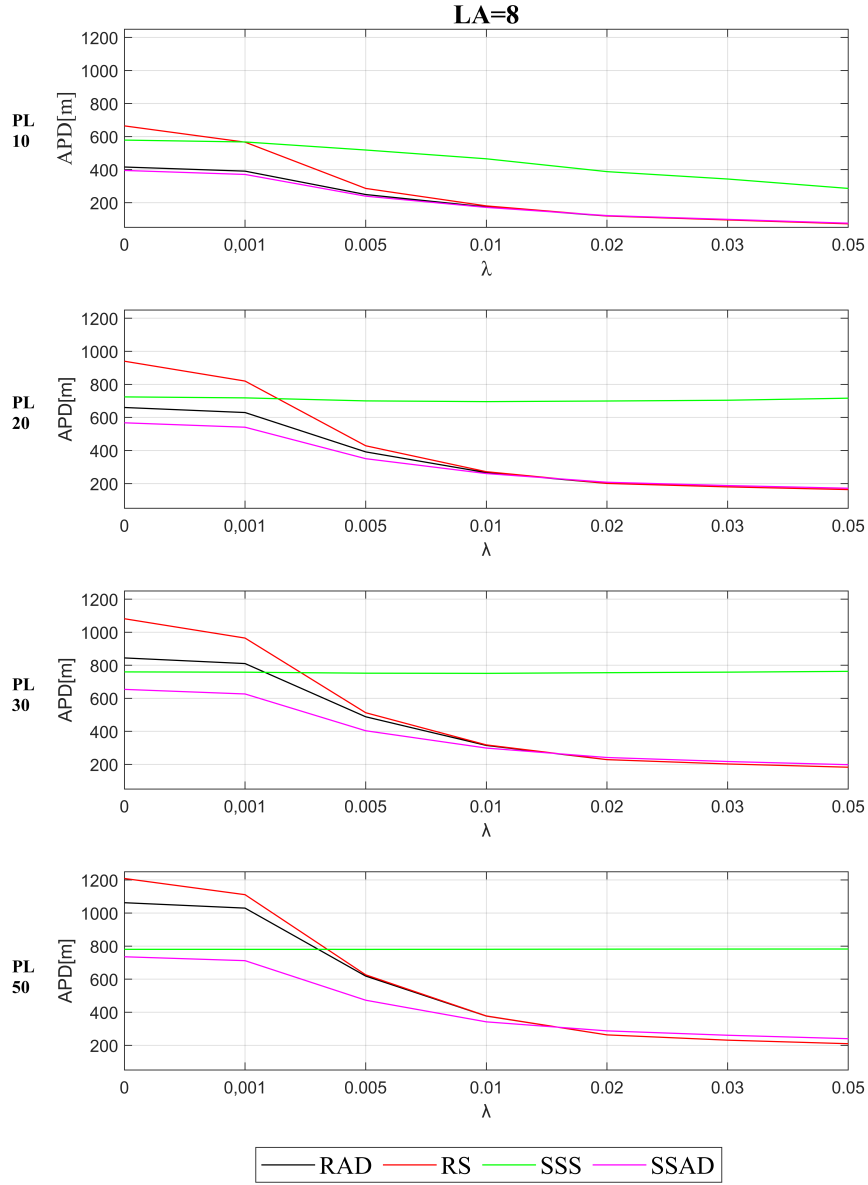


Figure 2.26: Plotting Single Central Picking configuration and $LA = 8$.

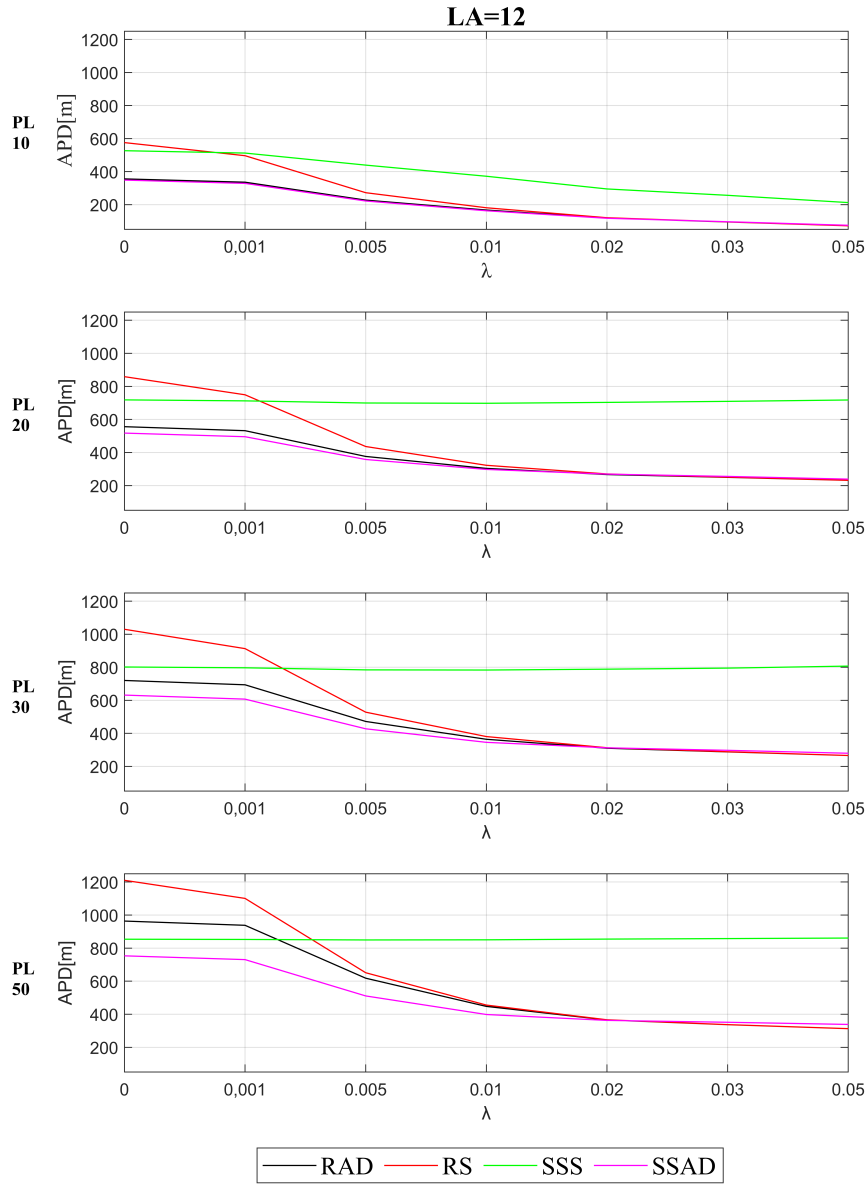


Figure 2.27: Plotting Single Central Picking configuration and $LA = 12$.

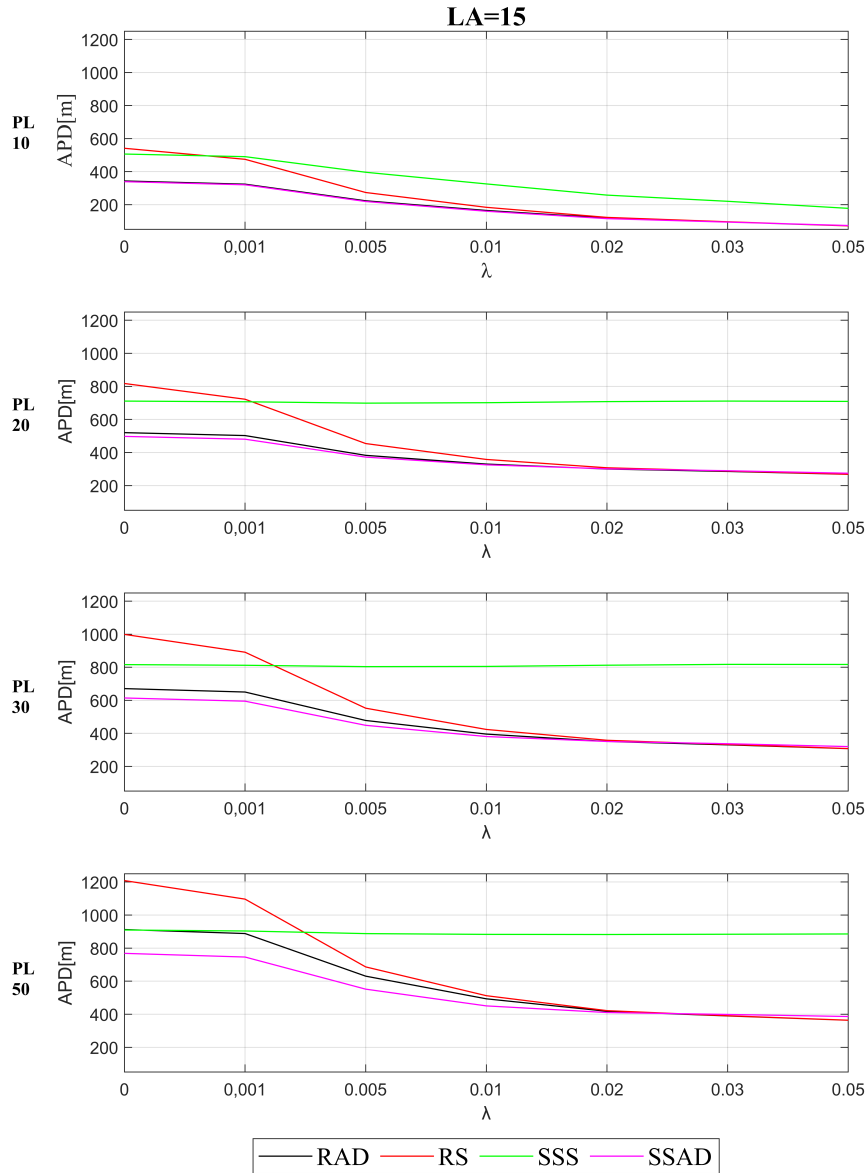


Figure 2.28: Plotting Single Central Picking configuration and $LA = 15$.

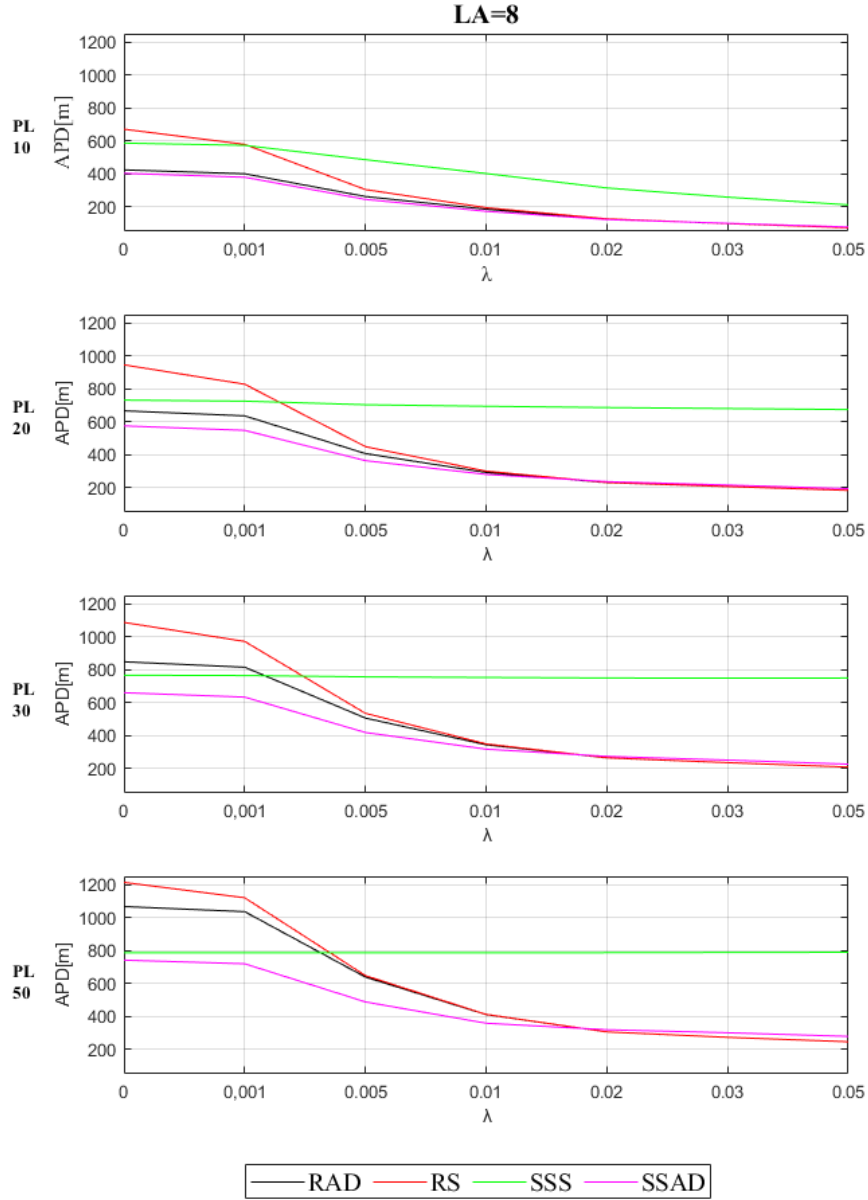


Figure 2.29: Plotting Single Lateral Picking configuration and $LA = 8$.

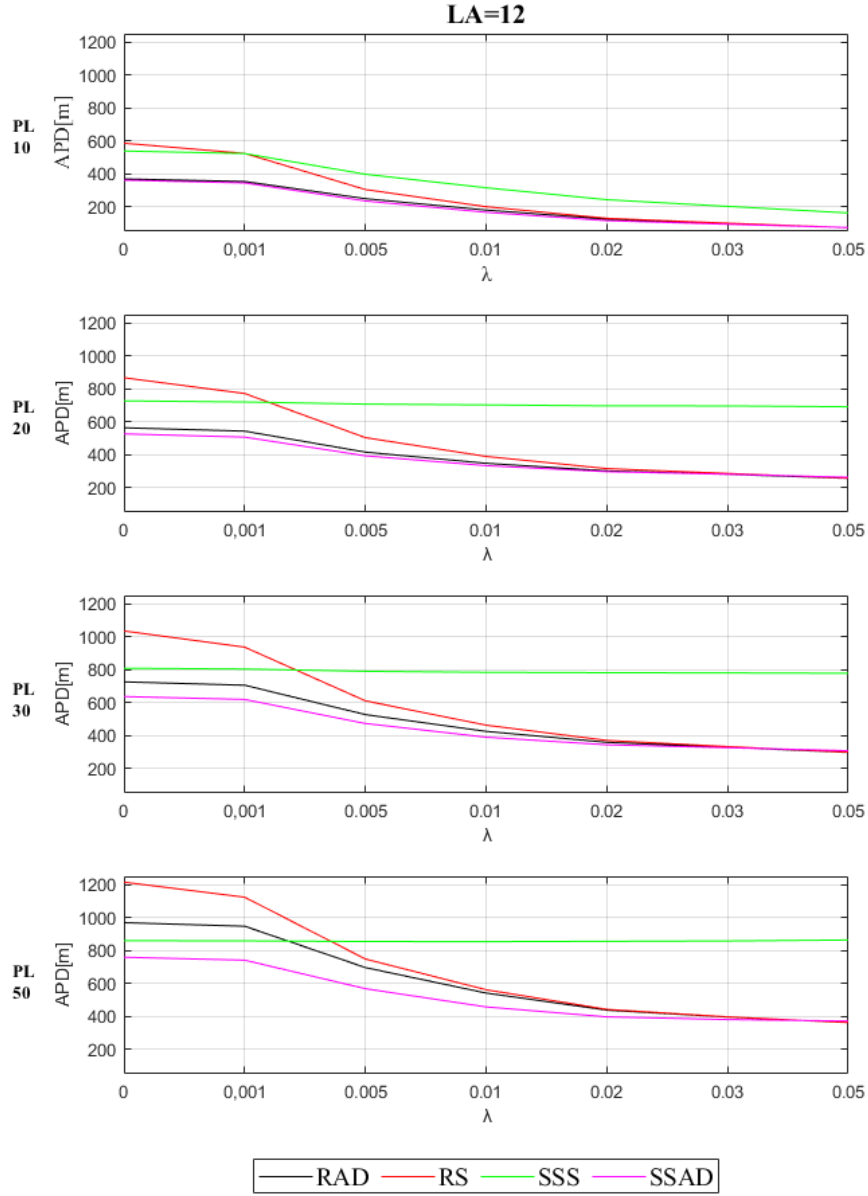


Figure 2.30: Plotting Single Lateral Picking configuration and $LA = 12$.

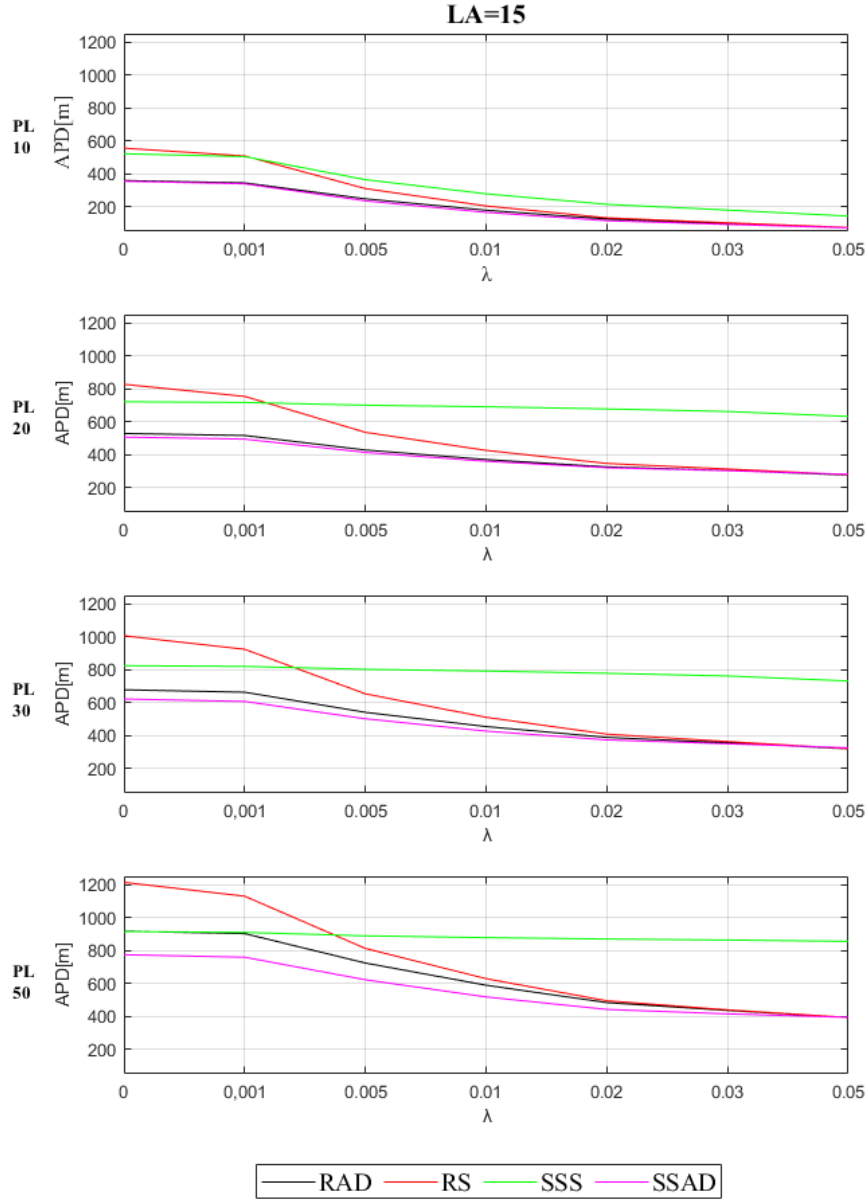


Figure 2.31: Plotting Single Lateral Picking configuration and $LA = 15$.

The *APD* values of the *RS*, *RAD*, and *SSAD* routing policies with $\lambda \geq 0.01$ are summarised in Table 2.8 and Table 2.9 for the two selected *I/O* configurations. The Δ value, intended as the percentage deviation between the maximum and minimum *APD* values (Equations 2.16-2.17-2.18), has also been added to these two tables for a more effective comparison of the routing policies.

$$M = \max [APD |_{RP=RS}, APD |_{RP=RAD}, APD |_{RP=SSAD}] \quad (2.16)$$

$$m = \min [APD |_{RP=RS}, APD |_{RP=RAD}, APD |_{RP=SSAD}] \quad (2.17)$$

$$\Delta = \frac{(M - m)}{m} \cdot 100 \quad (2.18)$$

The Δ parameter allows for evaluating the range of *APD* values as the *RP* varies; $\Delta \leq 10\%$ was considered a small deviation.

Concerning the *SCP* configuration, it can be seen that only 9 scenarios out of 144 considered were characterized by $\Delta > 10\%$, while in the case of *SLP*, 18 scenarios out of 144 had $\Delta > 10\%$. Among the policies analysed, *RS* differs from *RAD* and *SSAD* in the fact that it does not make use of either the *CA* or the corridor at the bottom. This is an important aspect to consider in specific operational contexts, where the removal of such aisles could favour an increase in warehouse capacity or a decrease in the area occupied. These variations in the layout could be implemented without compromising the necessary storage capacity nor the efficiency of the picking process in terms

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Table 2.8: APD [m] values in SCP configuration for $\lambda \geq 0.01$.

LA=8						LA=12						LA=15						
PL=10	λ	RP				λ	RP				λ	RP						
		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ			
		0.01	180	174	171		5.3%	0.01	181	167		163	11.2%	0.01	184	165	160	14.9%
		0.02	119	119	122		2.1%	0.02	121	118		117	2.8%	0.02	123	118	115	6.6%
		0.03	95	95	99		3.6%	0.03	96	95		97	1.5%	0.03	96	95	94	2.2%
		0.05	72	72	76		5.2%	0.05	72	72		75	4.5%	0.05	72	72	74	3.0%
PL=20	λ	RP				λ	RP				λ	RP						
		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ			
		0.01	272	266	260		4.3%	0.01	323	304		298	8.4%	0.01	358	330	325	10.0%
		0.02	201	201	208		3.6%	0.02	270	267		269	1.4%	0.02	307	300	301	2.5%
		0.03	180	180	188		4.5%	0.03	251	250		255	2.2%	0.03	288	285	290	1.5%
		0.05	164	164	172		5.0%	0.05	232	231		239	3.2%	0.05	268	268	275	2.4%
PL=30	λ	RP				λ	RP				λ	RP						
		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ			
		0.01	318	315	299		6.4%	0.01	380	364		345	10.1%	0.01	424	395	381	11.3%
		0.02	229	229	241		5.6%	0.02	313	310		312	1.0%	0.02	358	351	351	2.1%
		0.03	202	202	217		7.3%	0.03	288	288		297	3.3%	0.03	333	330	337	2.1%
		0.05	183	183	198		8.4%	0.05	266	266		279	5.1%	0.05	308	307	320	4.0%
PL=50	λ	RP				λ	RP				λ	RP						
		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ			
		0.01	378	377	342		10.5%	0.01	455	447		398	14.3%	0.01	512	493	450	13.7%
		0.02	263	263	287		9.2%	0.02	366	365		363	1.0%	0.02	422	418	410	2.8%
		0.03	231	231	261		12.9%	0.03	337	337		351	4.3%	0.03	391	390	399	2.3%
		0.05	210	210	240		14.5%	0.05	313	313		338	8.2%	0.05	364	364	386	6.2%

of APD . Moreover, RS is a very simple policy and can be considered the easiest logic to be understood and implemented by a picker. Consequently, when adopting this policy, it will also be easier to obtain a simple route for the picker to take during the order processing; the possibility of incorrect routing is therefore reduced, with a benefit on the overall process efficiency and effectiveness.

On the other hand, looking again at Figures 2.26-2.27-2.28 and Figure 2.29-2.30-2.31, it is easy to see that for scenarios with $\Delta < 0.01$ (which are more likely to be observed in real environments), the best routing policy overall is the $SSAD$, as demonstrated by the APD value shown in Tables

Table 2.9: APD [m] values in SLP configuration for $\lambda \geq 0.01$.

LA=8					LA=12					LA=15								
PL=10	λ	RP				λ	RP				λ	RP						
		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ			
		0.01	193	184	171		12.9%	0.01	199	179		165	20.5%	0.01	204	178	165	23.5%
		0.02	125	124	121		3.4%	0.02	129	124		115	12.3%	0.02	132	124	114	15.3%
		0.03	97	97	99		1.7%	0.03	99	98		93	7.0%	0.03	102	99	92	10.7%
		0.05	71	71	76		6.6%	0.05	72	72		73	1.0%	0.05	73	73	71	3.6%
PL=20	λ	RP				λ	RP				λ	RP						
		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ			
		0.01	299	291	279		7.2%	0.01	389	347		332	16.9%	0.01	425	370	359	18.4%
		0.02	230	229	235		2.6%	0.02	314	301		296	6.3%	0.02	346	325	320	8.2%
		0.03	206	206	215		4.4%	0.03	285	280		280	2.0%	0.03	312	303	302	3.4%
		0.05	182	182	193		5.5%	0.05	257	256		262	2.4%	0.05	278	276	280	1.6%
PL=30	λ	RP				λ	RP				λ	RP						
		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ			
		0.01	348	343	316		10.0%	0.01	462	424		389	18.8%	0.01	510	454	426	19.7%
		0.02	264	264	273		3.4%	0.02	369	358		343	7.7%	0.02	408	388	373	9.4%
		0.03	234	234	250		6.6%	0.03	332	328		325	2.0%	0.03	362	355	349	3.8%
		0.05	208	208	225		8.6%	0.05	298	297		307	3.3%	0.05	320	319	324	1.9%
PL=50	λ	RP				λ	RP				λ	RP						
		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ		RS	RAD	SSAD	Δ			
		0.01	411	410	358		15.0%	0.01	561	541		457	22.9%	0.01	628	588	517	21.5%
		0.02	305	305	318		4.4%	0.02	442	437		396	11.5%	0.02	494	483	441	11.8%
		0.03	272	272	300		10.3%	0.03	396	395		380	4.3%	0.03	439	435	414	5.9%
		0.05	245	245	278		13.3%	0.05	362	362		371	2.6%	0.05	392	392	393	0.3%

2.10-2.11.

One of the most interesting findings of the study, in the authors' opinion, concerns the impact of the heterogeneity in the market demand on the choice of the optimal routing policy. Other important outcomes concern the difference in that impact as a function of the RP considered; indeed, depending on the heterogeneity of demand, different RPs can be identified as optimal, which ultimately, can influence the hardware characteristics of the warehouse. This line of reasoning is summarised in Figure 2.32. In particular, with $\lambda \geq 0.01$ (right side of the graph), the RS policy turns out to be optimal; as that policy does not make use of CAs , their presence will not

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Table 2.10: APD [m] values in SCP configuration for $\lambda < 0.01$.

LA=8					LA=12					LA=15							
PL=10	RP				λ	RP				λ	RP						
	RS	RAD	SSS	SSAD		RS	RAD	SSS	SSAD		RS	RAD	SSS	SSAD			
	~ 0	665	416	579		395	~ 0	576	356		526	348	~ 0	541	343	506	339
	0.001	566	391	567		371	0.001	496	336		512	329	0.001	474	324	490	320
	0.005	286	249	519		239	0.005	272	227		439	222	0.005	273	223	396	219
PL=20	RP				λ	RP				λ	RP						
	RS	RAD	SSS	SSAD		RS	RAD	SSS	SSAD		RS	RAD	SSS	SSAD			
	~ 0	940	660	724		567	~ 0	859	556		718	517	~ 0	817	520	711	497
	0.001	820	630	718		541	0.001	749	532		712	495	0.001	722	502	707	480
	0.005	429	392	700		350	0.005	436	376		699	358	0.005	454	383	698	372
PL=30	RP				λ	RP				λ	RP						
	RS	RAD	SSS	SSAD		RS	RAD	SSS	SSAD		RS	RAD	SSS	SSAD			
	~ 0	1082	844	760		654	~ 0	1030	720		802	631	~ 0	999	671	816	614
	0.001	965	810	758		626	0.001	913	694		797	607	0.001	891	650	812	595
	0.005	513	488	752		403	0.005	528	472		784	427	0.005	552	478	804	448
PL=50	RP				λ	RP				λ	RP						
	RS	RAD	SSS	SSAD		RS	RAD	SSS	SSAD		RS	RAD	SSS	SSAD			
	~ 0	1209	1062	780		735	~ 0	1210	964		854	753	~ 0	1208	912	909	768
	0.001	1111	1030	780		712	0.001	1101	938		852	730	0.001	1096	888	904	746
	0.005	626	619	780		473	0.005	651	618		849	511	0.005	686	630	888	552

affect the performance of the picking process and, consequently, CAs could be removed from the warehouse. On the contrary, with $\lambda < 0.01$ (left side of the graph), the implementation of policies which instead make use of cross aisles ($SSAD$) increases the performance of the warehouse, being the best policy in all scenarios considered for these demands from the market.

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Table 2.11: APD [m] values in SLP configuration for $\lambda < 0.01$.

$LA=8$					$LA=12$					$LA=15$							
$PL=10$	RP				λ	RP				λ	RP						
	RS	RAD	SSS	$SSAD$		RS	RAD	SSS	$SSAD$		RS	RAD	SSS	$SSAD$			
	~ 0	670	423	586		402	~ 0	585	368		538	361	~ 0	555	358	521	354
	0.001	578	400	572		378	0.001	523	353		522	344	0.001	507	344	504	338
	0.005	304	261	485		244	0.005	304	248		396	234	0.005	309	247	363	235
$PL=20$	RP				λ	RP				λ	RP						
	RS	RAD	SSS	$SSAD$		RS	RAD	SSS	$SSAD$		RS	RAD	SSS	$SSAD$			
	~ 0	945	665	730		574	~ 0	866	563		726	525	~ 0	827	528	721	506
	0.001	827	635	724		547	0.001	771	542		719	506	0.001	753	516	716	494
	0.005	448	406	703		363	0.005	503	415		706	392	0.005	535	428	700	413
$PL=30$	RP				λ	RP				λ	RP						
	RS	RAD	SSS	$SSAD$		RS	RAD	SSS	$SSAD$		RS	RAD	SSS	$SSAD$			
	~ 0	1086	847	766		659	~ 0	1035	725		808	636	~ 0	1005	677	823	621
	0.001	971	814	764		633	0.001	936	705		803	618	0.001	923	662	819	606
	0.005	534	505	756		418	0.005	610	526		789	472	0.005	652	540	801	501
$PL=50$	RP				λ	RP				λ	RP						
	RS	RAD	SSS	$SSAD$		RS	RAD	SSS	$SSAD$		RS	RAD	SSS	$SSAD$			
	~ 0	1213	1066	786		741	~ 0	1215	968		859	758	~ 0	1213	917	915	774
	0.001	1120	1035	786		719	0.001	1123	947		858	741	0.001	1129	902	909	758
	0.005	647	638	786		487	0.005	748	696		854	567	0.005	812	723	888	622

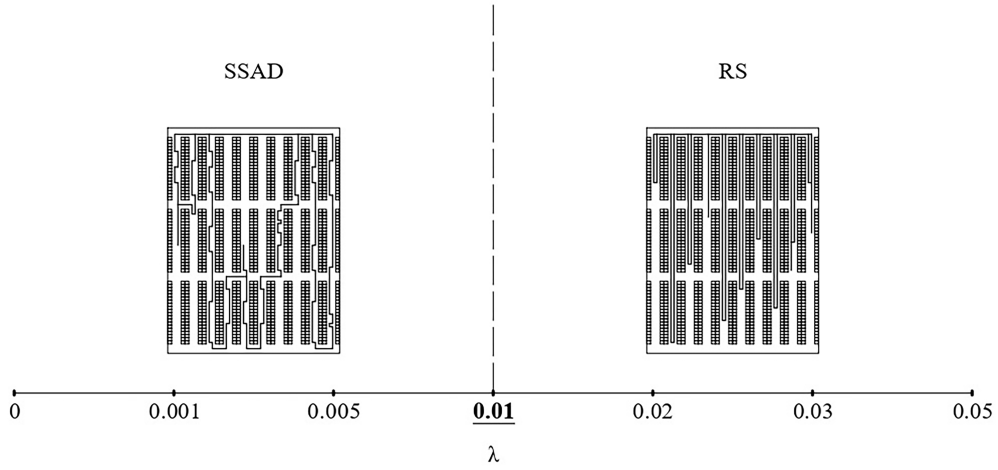


Figure 2.32: Optimal routing policy based on λ value.

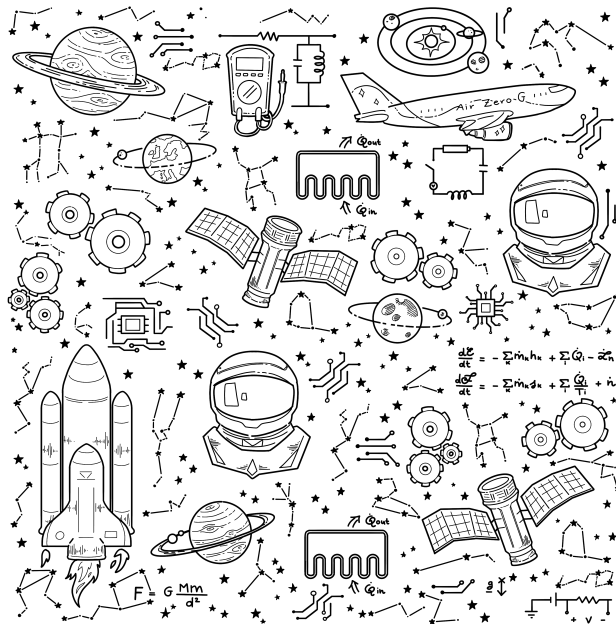
2.3 Results and discussion

In the present study, a simulation *tool* was created to reproduce a manual picking process in a traditional double-side rack warehouse. The ultimate objective of the study was to investigate different warehouse configurations, by varying both software (RP , PL , λ) and hardware (x_f , CA , w , N , α , β , I/O) parameters of the system, exploiting the simulation *tool*, and to analyse their impact on the resulting APD . In line with the approach by Manuj et al., 2009, the starting point for developing the model was the problem formulation, followed by the definition of the independent and dependent variables. Then, a simulation campaign was carried out using the model, with results averaged on 10,000 replicates for each configuration considered. During each simulation, the picking lists were varied. By analysing a set of selected scenarios out of the whole set of data obtained through simulation, two key results relating to the RPs were observed. In the case of low λ values, reflecting a homogeneous demand of items (and implicitly, random storage), the best policy turned out to be $SSAD$. This result corroborates the findings by Bottani et al., 2019a, who reported that the $SSAD$ policy is effective under various warehouse configurations. However, with high λ values, i.e., strongly heterogeneous demand, $SSAD$, RAD and RS all exhibit comparable performance. This outcome has various implications. First, it highlights that the heterogeneity in demand, as modelled in this study, affects the picker routing, and thus, this aspect is to be taken into account when trying to optimize the order picking process. As a second point, the fact that more policies return the same travel distance also indicates that, with

a correct item allocation, the usage of a specific routing policy becomes indifferent. Ultimately, this introduces the consideration that if products have markedly different behaviours, a correct item allocation is to be prioritized over the choice of the routing policy. This is an important practical aspect, as changing the allocation of items in the warehouse is a costly activity, which takes days of work and cannot be made frequently; therefore, carefully evaluating the allocation of the items and keeping it unchanged is critical to the efficiency of the system. Additional analyses are nonetheless recommended for the future to investigate this point in greater detail. As far as the three policies with similar behaviour, again from a practical perspective, it could be reasonable to privilege the implementation of the *RS* logic, which not only generates very easy routes for the picker but also does not require the *CA*. Although not evaluated in this study, it is known that an easier route often corresponds to a lower probability of human errors, which further favours the implementation of the *RS* policy. The *SSS* policy is instead an exception and shows an anomalous behaviour; by the way, researchers have already indicated that this policy is unlikely to be effective (C. G. Petersen, 1999), as the picker is always forced to traverse the whole corridor to pick the items of the picking list, resulting in longer routes (Bottani et al., 2019a). Building on this work, it is recommended to take future research activities focusing on the study of other *I/O* configurations, the comparative evaluation of the impact of scattered storage *vs* dedicated storage, or, as mentioned above, the quantitative evaluation of the impact of human errors on the efficiency of the order picking process. These analyses could be effectively supported by the simulation *tool* presented in this Second Chapter.

Chapter 3

Experiments in Microgravity



Nomenclature and acronyms

The nomenclature and acronyms used in Chapter 3 are presented in Table 3.1.

Table 3.1: Nomenclature and acronyms used in Chapter 3.

Symbol	Description	Unit
<i>ISS</i>	International Space Station	—
<i>ESA</i>	European Space Agency	—
<i>ER</i>	Experimental Report	—
<i>PFC</i>	Parabolic Flight Campaign	—
<i>PHP</i>	Pulsating Heat Pipe	—
<i>FPPHP</i>	Flat Plate PHP	—
<i>HG</i>	Hyper Gravity	m/s^2
<i>LG</i>	Micro Gravity	m/s^2
<i>g</i>	Acceleration due to gravity	m/s^2
J_x	X-axis acceleration magnitude	m/s^2
J_y	Y-axis acceleration magnitude	m/s^2
J_z	Z-axis acceleration magnitude	m/s^2
<i>r</i>	Radius	<i>mm</i>
<i>v</i>	Velocity	m/s
F_c	Centrifugal Force	<i>N</i>
a_c	Centripetal Acceleration	m/s^2
<i>Bo</i>	Bond number	—
ρ	Density	kg/m^3

c_p	Specific Heat	$J/(kg \cdot K)$
T	Temperature	K
T_{env}	Environment Temperature	K
R	Thermal Resistance	K/W
R_{env}	Overall heat-transfer Thermal Resistance	$m^2 \cdot K/W$
$R(t)$	Instantaneous Thermal Resistance	K/W
t	Time	s
d	Diameter of the tube	mm
d_{int}	Internal diameter of the <i>PHP</i>	mm
d_{ext}	External diameter of the <i>PHP</i>	mm
L_{coil}	Total coil length of the <i>PHP</i>	mm
r_{int}	Internal radius of the <i>PHP</i>	mm
r_{ext}	External radius of the <i>PHP</i>	mm
q	Heat flux per unit surface	W/m^2
σ	Surface tension of the fluid	N/m
<i>PCB</i>	Printed Circuit Board	—
<i>FR</i>	Filling Ratio	%
<i>IR</i>	Infra Red	—
<i>PLA</i>	Polylactic Acid	—
<i>TC</i>	Thermocouple	—

3.1 Experiments in Altered Gravity

Experiments in altered gravity are studies conducted under conditions where the effect of gravity on matter differs from that experienced on Earth. These experiments can be carried out in both microgravity conditions (such as on space stations or satellites) and hypergravity conditions (such as in the centrifugal). The realm of experiments in altered gravity is highly compelling as gravity plays a fundamental role in biological, physical, and chemical processes occurring on Earth. Hence, the opportunity to examine how these processes are influenced by varying gravity conditions can provide valuable scientific insights.

Research in biology and biomedicine conducted in space provides valuable insights into how altered gravity affects cells, tissues, and organisms. These experiments help to understand the broader impact of different values of gravity on human health and biological processes, including growth, bone formation, cardiovascular health, metabolism, immune response, and other biological functions (Davis et al., 2024; Ferranti et al., 2021). The study of fluid dynamics in space also yields critical information. Observing fluid behavior in altered gravity conditions allows scientists to investigate the flow properties of liquids and gases without the influence of terrestrial gravity (Langbein, 1990). In the field of materials science, experiments performed under altered gravity conditions are crucial for understanding material formation processes, such as solidification and diffusion (Kargl et al., 2013). Additionally, the evaluation of new technologies, such as additive manufacturing in microgravity, can enhance our understanding of both the technology

and the behavior of the materials involved. Gravity, or the lack thereof, significantly impacts these processes, underscoring the importance of studying materials in space environments (Jarosch et al., 2023). Finally, conducting experiments to evaluate the performance of materials and technological devices under altered gravity presents significant challenges. Addressing these challenges is essential for the advancement of cutting-edge technologies, as understanding the effects of microgravity and hypergravity on technological systems is critical for future innovations (Ostrach, 2008). It is important to note that experiments under microgravity gravity conditions can be conducted using various platforms. To achieve microgravity, platforms such as the International Space Station (*ISS*), Suborbital Flights, Parabolic Flight Campaigns (*PFC*), and Drop Towers are utilized. Also included are sounding rockets, which, unlike previous platforms, are typically destructive experiments (Okninski et al., 2015). These platforms provide different periods of microgravity: starting from approximately 22 seconds during *PFC* to a sustained microgravity environment aboard the *ISS*. In contrast, to simulate and investigate the effects of hypergravity, large-diameter centrifuges are employed (Callens et al., 2010).

In this third Chapter, the implementation and preliminary analysis of the data regarding a passive heat exchanger under altered gravity conditions will be presented.

3.1.1 Parabolic Flight Campaign

Parabolic Flight Campaigns (*PFC*) entail the execution of parabolic maneuvers by specialized aircraft to induce periods of microgravity, or weightlessness, within a controlled environment. These campaigns offer researchers the opportunity to conduct experiments, validate equipment, and simulate space conditions without the constraints of terrestrial gravity. *PFC* are characterized by their utilization of modified aircraft capable of executing parabolic trajectories. Each parabola consists of a controlled ascent followed by a rapid descent, during which occupants experience brief periods of weightlessness. The duration and quality of microgravity experienced during these parabolas make *PFC* an attractive platform for conducting experiments that require a gravity-free environment. Additionally, the controlled nature of these flights allows for repeated experimentation and validation of results. The scientific significance of *PFC* lies in their ability to provide researchers with access to microgravity conditions, enabling investigations into phenomena influenced by gravity. Furthermore, these campaigns serve as a crucial precursor to space missions, allowing researchers to refine experimental protocols and validate equipment before deployment in space.

3.1.1.1 Parabolic manoeuvres

In the Figure 3.1, the manoeuvre performed by the aircraft during the *PFC* is shown. During these manoeuvres, the aircraft follows a curved trajectory that induces short periods of microgravity, allowing the occupants to experience weightlessness similar to that observed in space.

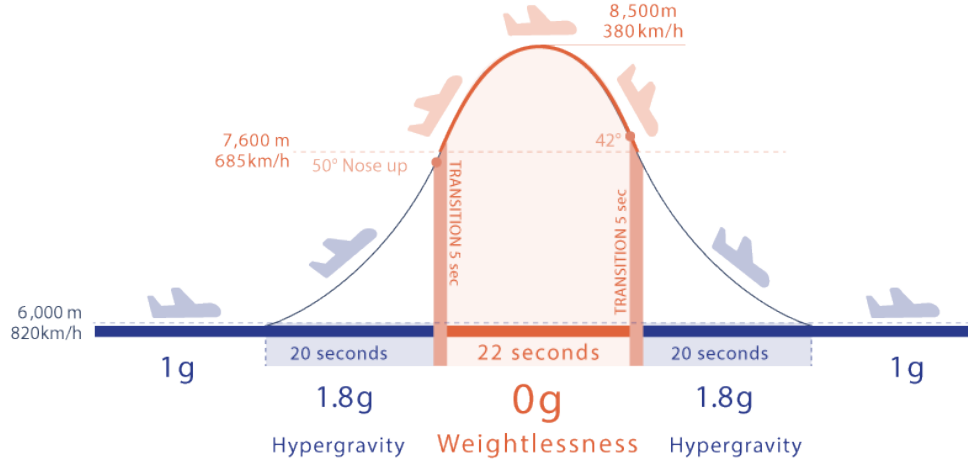


Figure 3.1: ESA Parabolic manoeuvres. Image is copyrighted by Novespace, which retains full ownership and intellectual property rights.

During parabolic flights, the centripetal acceleration a_c and the related centrifugal force F_c are crucial for achieving microgravity conditions. To balance these forces with the gravitational acceleration g , the result is as follow:

$$\frac{v^2}{r} = g \quad (3.1)$$

The solution of the Equation 3.1 for the variable v yields the necessary velocity to establish microgravity conditions throughout the parabolic trajectory. During this maneuver, the aircraft undergoes a parabolic trajectory, where it ascends steeply before descending rapidly, creating a temporary

state of apparent weightlessness for approximately 22 seconds. To execute this maneuver safely and precisely, three pilots are required, with each one is responsible for controlling one axis of the aircraft: pitch, roll, and yaw.

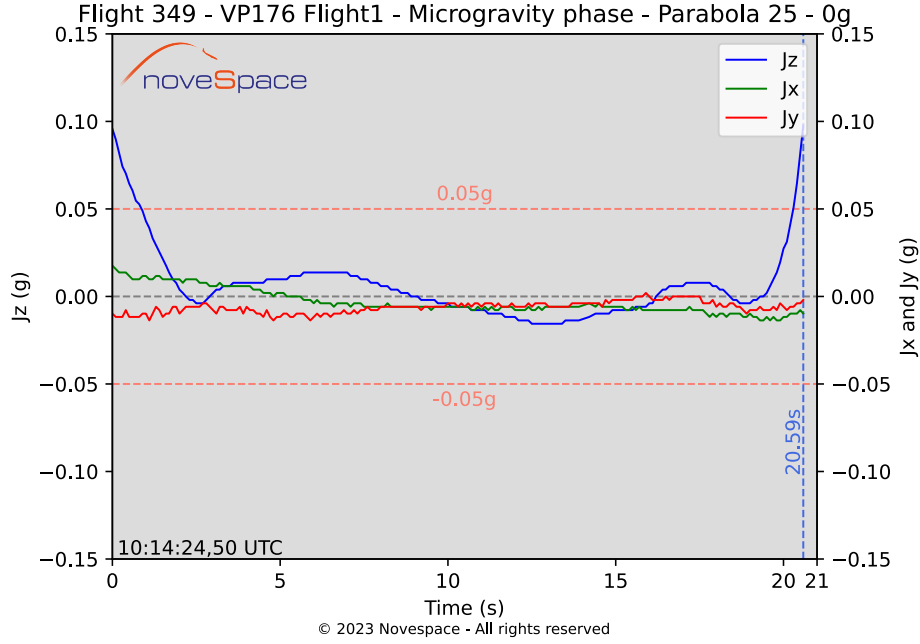


Figure 3.2: Novespace post-flight data, 83th ESA PFC D1, Parabola n° 25.

Figure 3.2 presents the post-flight acceleration data for parabola n° 25, provided by Novespace, from the Day 1 of the 83th ESA *PFC* of November 2023.

The pilot in charge of the pitch axis controls the upward and downward movements of the aircraft, ensuring the steep ascent and descent required for the parabolic trajectory. The pilot managing the roll axis maintains the lateral stability of the aircraft during the maneuver, preventing excessive banking or tilting. Finally, the pilot responsible for the yaw axis maintains

the aircraft's heading and directional stability throughout the maneuver. Through coordinating their efforts, the three pilots work together to precisely execute the parabolic flight maneuver, enabling researchers and passengers on board to experience short periods of microgravity as well as low-gravity conditions for the purpose of scientific experimentation or astronaut training. In fact, by varying the trajectory and speed of the aircraft, low-gravity conditions similar to those found on the Moon or Mars (Table 3.2) can also be simulated on these platforms, thus expanding the range of experimental possibilities for studying environments with different gravitational forces (Farina et al., 2024).

Table 3.2: Gravitational acceleration in different environment.

Environment	Gravity Acceleration
Earth	9.81 m/s^2
Moon	1.62 m/s^2
Mars	3.71 m/s^2
Space	$\sim 0.00 \text{ m/s}^2$

3.2 PFC Case study

3.2.1 Pulsating Heat Pipe

A Pulsating Heat Pipe (*PHP*), is a passive thermal control device, it is lightweight and does not require an external power supply or control. As pointed out in the work of Mameli et al., 2022, these features make it an interesting tool for spacecraft thermal management. *PHPs* are one of the most interesting heat exchange devices. Due to their ability to work passively, they do not require controls or an energy source. These devices are characterized by small tubes and the absence of wick structures, making them easy to manufacture and highly adaptable to confined spaces. These characteristics are strategically advantageous for various applications, particularly in the cooling of electrical systems. The *PHP* idea is quite recent, initially designed by Akachi, 1990, which defined this device as a "*...loop-type heat pipe in which a heat-carrying fluid [...], circulates in a loop form in itself under its own vapor pressure at high speed within an elongate pipe so as to repeat vaporization and condensation, thus carrying out a heat transfer*".

Various designs and technologies have been developed to enhance the performance and lower the weight and power requirements of thermal control devices (Gilmore, 2002). Among the many options, *PHP* represents a significant advancement in thermal management. In light of this, *PHPs* are receiving growing academic and industrial interest thanks to some fascinating features, such as good flexibility, high reliability and low manufacturing cost for both ground and space applications (Nikolayev and Marengo, 2018; Mangini et al., 2015). Depending on their geometry, *PHPs* can be mainly

classified as tubular *PHPs* or flat-plate *PHPs* (*FPPHPs*) (Bastakoti et al., 2018).

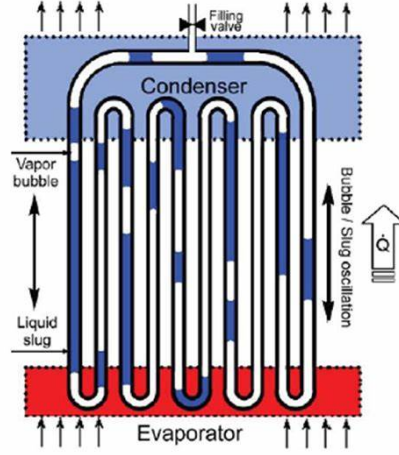


Figure 3.3: Typical PHP layout (Wong et al., 2007).

In these passive systems, fluid flow is driven by temperature variations between the evaporator and the cooled section (condenser), with an adiabatic section in between, rather than relying on external devices like pumps, as shown in Figure 3.3. The fluid, being primarily saturated, experiences thermal instabilities that create pressure differences, which then serve as the driving force for its self-sustained movement (Marengo and Nikolayev, 2018). This self-sustained motion is further facilitated by capillarity, which plays a crucial role in promoting the return of the condensed fluid to the evaporator, thereby ensuring continuous heat transfer and maintaining the cycle of evaporation and condensation within the *PHP*.

3.2.1.1 Key parameters

The performance of a *PHP* is influenced by several key factors, including the geometry of the device, its orientation and the properties of the working fluid. Each of these parameters plays a crucial role in determining the overall thermal efficiency and operational stability of the system (Zhang and Faghri, 2008).

3.2.1.1.1 Internal Diameter

The internal diameter of the pipe is the primary geometrical parameter to consider in the design of a *PHP*. To work effectively as a *PHP*, it is crucial to maintain capillary flow in all the working conditions. This condition can only be met if the internal diameter remains below a critical threshold. The criterion for the capillary limit is established using the dimensionless Bond number, as defined in Equation 3.2.

$$Bo < 4; \quad Bo = \frac{g(\Delta\rho)d^2}{\sigma} \quad (3.2)$$

Where g is the acceleration due to gravity, $\Delta\rho$ is the difference of densities of the liquid and vapor phases, respectively, d is the internal diameter of the channel, and σ is the surface tension of the fluid. All the listed fluid properties should be evaluated based on the average fluid temperature during the *PHP* operation, considering the fluid in saturation conditions unless the fluid temperature/pressure is locally known in the device through direct fluid measurements.

The Bond number (Bo), is a dimensionless number that characterizes the

relative importance of gravity to surface tension forces in a fluid system. Bo quantifies the relative influence of gravitational forces compared to surface tension forces in the operation of these devices. A high Bo signifies that gravitational effects are predominant over surface tension forces, thereby significantly affecting the design and geometrical configuration of the devices.

Rearranging Equation 3.2, the definition of the capillary limit based on the critical diameter, which depends on the gravitational field and the properties of the working fluid, is as follows in Equation 3.3:

$$d_{\text{crit}} = 2\sqrt{\frac{\sigma}{g(\Delta\rho)}} \quad (3.3)$$

Bond number plays a key role in the design of a *PHP*. The internal diameter must be chosen to ensure that the fluid flow remains capillary. As seen in the Equation 3.3, d_{crit} is inversely proportional to the acceleration of gravity. In light of this, *PHPs* for space applications can be designed with larger diameters than the ones designed for terrestrial applications. In microgravity, gravitational effects are minimal and allow for a larger inner diameter while maintaining effective capillary action. Therefore, the design of *PHPs* for space applications can take advantage of this feature to optimize its performance.

3.2.1.1.2 Evaporator and Condenser Sizing

These parameters can influence the overall heat transfer of the *PHP* and alter the flow patterns within the heat pipe. Below a certain onset heat flux from the evaporator, the fluid in the *PHP* will not pulsate. Additionally, if

the condenser is unable to dissipate sufficient heat, it will limit the maximum heat transfer achievable by the *PHP*.

3.2.1.1.3 Number of turns or loops

Increasing the number of turns or loops in a *PHP* increases length of the liquid and vapour interfaces, enhancing the heat transfer area. More loops generally improve performance by providing additional pathways for fluid motion.

3.2.1.1.4 Orientation

The orientation of the *PHP* with respect to gravity plays an important role in its performance. Vertical or inclined orientation allows gravity to help maintain oscillation and circulation, resulting in better thermal performance. In contrast, in the absence of gravity, such as under microgravity conditions, *PHP* performance relies solely on capillary forces and internal fluid dynamics. Gravitational forces play a key role in determining the operational efficiency and functionality of *PHP*. Studies have been conducted to evaluate the performance of *PHPs* on the ground, varying the operating angle of the device (Ricci, 2023), highlighting how gravitational forces the operation of these devices (Pagliarini et al., 2021b).

3.2.1.1.5 Working Fluid Properties

The selection of the working fluid is crucial, as its properties directly affect the performance of the *PHP*. The main factors to consider are the *latent*

heat, surface tension, specific heat, viscosity, and the pressure-temperature derivative ($\frac{\partial P}{\partial T}|_{sat}$), summarised in Table 3.3.

Table 3.3: Summary of Key Fluid Properties.

Property	Definition	Unit
Latent Heat	Heat required for phase change without temperature change.	J/kg
Surface Tension	Force per unit length acting at the surface of a liquid.	N/m
Specific Heat	Heat required to raise the temperature of a unit mass by one degree.	$J/kg \cdot K$
Viscosity	Resistance of a fluid to flow or deformation.	$Pa \cdot s$
Pressure-Temperature Derivative	Change in pressure with respect to temperature at saturation.	Pa/K

Fluids with *low latent heat* promote faster evaporation and increased fluid motion for a given heat input, improving oscillations and thermal performance. However, this also increases the risk of *dry-outs* at lower heat loads. A *high surface tension* allows for larger inner tube diameters by increasing the critical diameter, thus enhancing the heat transfer area and the stored liquid volume. On the other hand, it also increases pressure drops, requiring higher thermal instabilities to maintain fluid motion. The rate of change in pressure with respect to temperature at saturated conditions $\frac{\partial P}{\partial T}|_{sat}$. This property affects the rate at which bubbles grow and collapse in response to temperature variations. At a high value of $\frac{\partial P}{\partial T}|_{sat}$, the difference between vapor pressures in the evaporator and condenser will increase, improving the performance of a *PHP* through enhanced oscillatory motion of liquid slugs.

Additionally, a *high specific heat* allows for greater sensible heat exchange, which is important for the overall heat transfer behavior in the *PHP*. However, a *low dynamic viscosity* will reduce shear stress along the wall and will consequently reduce pressure drop in the tube. This will reduce the heat input required to maintain a pulsating flow.

3.2.1.1.6 Filling Ratio

The Filling Ratio (FR), is the ratio between the volume of liquid inside a *PHP* and the total volume of the device. The limits of FR are 0% (empty device) and 100% (completely filled with liquid). At $FR = 0\%$, heat transfer occurs solely through conduction, rendering the device inefficient. At $FR = 100\%$, pulsations are inhibited, and heat is transferred ineffectively through both conduction and buoyancy. FR values close to these limits result in ineffective operation; an FR near 100% reduces the formation of vapor bubbles necessary for fluid motion, while a low FR leads to dry-out phenomena in the evaporator. It is considered that the optimal FR for a *PHP* is in range 20 – 80%, as it ensures a balance between the amounts of vapor and liquid, thus facilitating fluid movement and preventing premature dry-out.

3.2.2 Deployable PHP

A *Deployable* Pulsating Heat Pipe is the new milestone in the heat transfer field. In space applications, for example, *PHPs* are generally designed so that their capacitor section is connected to a radiator in order to improve heat dissipation by radiation. Radiators though, need to be *deployed* after the launch

of the spacecraft, and are liable of debris collision-induced damages. To give the radiator the possibility to fold back and so to have a cooling system that can protect itself would be a great step forward in space security and life extension of spacecrafts. The efficiency of the *deployable PHP* depends on the balance between its mechanical efficiency and the pressure drop caused by its geometrical features. Despite the characteristics of the first part of the balance being known, there is still much approximation for the fluid dynamics of it, due to the uncertainty caused by the pulsating behaviour of the fluid within the device. This uncertainty reflects also on the need for a microgravity experimental environment, being the gravity influence related to the variable and unpredictable density of the fluid along the device. In this chapter, the deployable pulsating heat pipe under microgravity conditions will be exposed. The study will make use of traditional acquisition systems, including thermocouples and pressure sensors, as well as a *non-contact* analysis technique through the use of a radiometric IR Camera. This study aims to provide an understanding of the behavior of the device in microgravity, specifically examining how the force of gravity affects its operation.

3.2.3 Thermography

Thermography is a *non-contact* technique for visualizing and analyzing the temperature distribution on the surface of an object (Livada et al., 2023). It works by detecting and recording infrared radiation emitted by objects, which is related to their temperature. The resulting image, known as a thermogram or infrared image, finds various applications, serving as a sign

of malfunction in mechanical and electrical maintenance, a health indicator in medical applications, and an indicator of heat loss in structures (Usamentiaga et al., 2014). In thermography, a device called thermal camera or infrared camera is used to capture the infrared radiation emitted by the object or scene. In addition, emissivity is critical in thermography, as it determines how effectively a material emits thermal radiation.

This value must be calculated accurately on the specific surface area of the material being analyzed, as emissivity directly affects the system's ability to accurately convert infrared radiation into temperature readings. Incorrect assessment of emissivity can lead to substantial discrepancies in results, thus undermining the reliability of thermal analyses (Balaras and Argiriou, 2002; Mineo and Pappalardo, 2021). To calculate the emissivity of a grey body, it is necessary to consider its ability to emit radiation relative to an ideal black body. Accurately defining this value requires experimental tests conducted at different known temperatures to evaluate the actual radiative emission and properly characterize the material (Bozzoli et al., 2011).

Thermography represents a particularly useful analysis technique in the study of *PHPs* as evidenced in the study of Pagliarini et al., 2022. This method offers several advantages over traditional measurement tools such as thermocouples and thermistors. Unlike the latter, thermography is not subject to thermal inertia, which can affect the accuracy of measurements, especially during transient phases of device operation. In addition, thermographic analysis does not locally alter the behavior of the system because it does not require direct contact with the device surface, thus avoiding interference with internal thermal or fluid dynamic flow. An additional advantage

of thermography is the ability to continuously and *non-intrusively* monitor the entire recorded area, allowing detailed and temporal characterization of the thermal behavior of the *PHP* as a function of operating conditions. Through infrared thermographic analysis, other studies have evaluated fluid oscillation frequencies within a metal *PHP*, tested at different thermal loads and orientations (Pagliarini et al., 2023). This technique made it possible to estimate local heat fluxes between the fluid and the walls of the device, providing a detailed understanding of fluid dynamics and heat transfer, without the need of direct visualizations of the fluid through transparent inserts, as already investigated in the study of Mangini et al., 2018.

3.3 DEPLOY! Project

The experiment related to the DEPLOY! Project (Figure 3.4) is an innovative Deployable Pulsating Heat Pipe that has already been tested once in a 2022 *PFC* inside the TOPDESS Project (Perna et al., 2024). This project represents a collaborative effort among three universities: Parma, Pisa, and Brighton. Other than the technological validation of the device in three dif-



Figure 3.4: DEPLOY! Project logo.

ferent unfolding configurations, several data on its thermal fluid dynamics behaviour in microgravity were collected. This experiment was then further developed by implementing an automation subsystem that allows the configuration of the device to be changed during testing. An IR Camera was added to analyse the thermal behaviour of the device from its surface temperature. The experiment aims to improve understanding of deployable *PHPs* by examining their performance in different configurations and temperatures. It also evaluates their behavior in the presence of varying gravitational forces, providing insights into their functionality under different operating conditions.

This experiment builds on the work conducted during the TOPDESS

Project, expanding its scope by investigating additional characteristics of the device. These newly explored aspects are essential to achieving a deeper understanding of both the scientific and technological behavior of the system, which will help drive improvements in its future applications.

his study specifically aims to offer a new analysis of the working parameters of a *PHP*. The main scientific and technological objective of this study is to provide an analysis of device behavior in multiple static opening angles and during dynamic opening in a microgravity environment.

3.3.1 Experiment description

The experimental setup shown in Figure 3.5 consists of two racks: the Experimental Box and the Control Rack, designed to ensure compliance with platform interface requirements and security regulations defined by Novespace, 2022. Inside the Experimental Box it is placed the Deployable *PHP*, fixed in a supporting structure. The containment box also houses the driver and thermal subsystem components, as well as an IR Camera.

The Control Rack serves as the management and monitoring center for the entire experiment and integrates power supplies, cooling systems, data acquisition, and drive management. These subsystems are designed to provide the necessary capabilities for test adjustment and essential data collection, thus enabling precise control and thorough evaluation of experimental variables. The Experimental Box and the Control Rack are shown in their final layout for the Parabolic Flight Campaign in Figure 3.6. In particular, the structure on the left refers to the Experimental Box, while the one on the

right corresponds to the Control Rack.

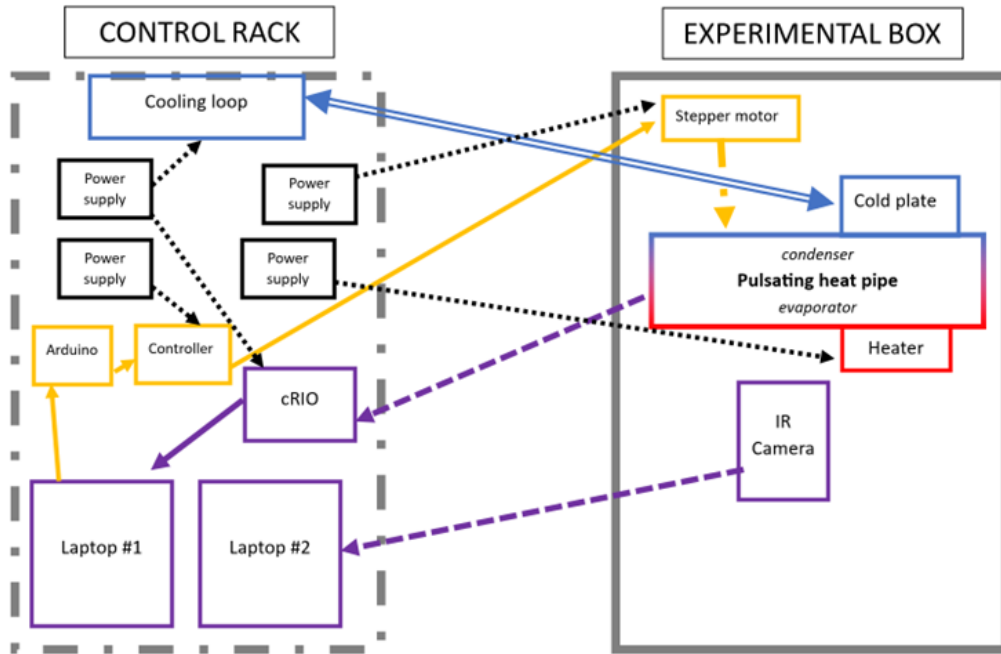


Figure 3.5: System block structure.

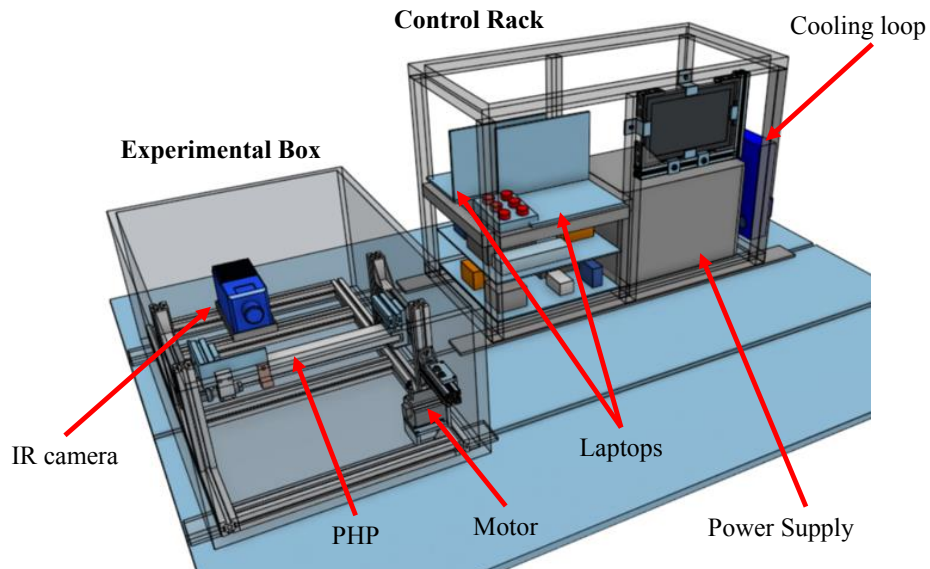


Figure 3.6: Experiment flight configuration.

3.3.1.1 Experimental Box

The Experimental Box (Figure 3.7) contains the Deployable *PHP*, the thermal subsystem, the automation subsystem and the data acquisition subsystem.

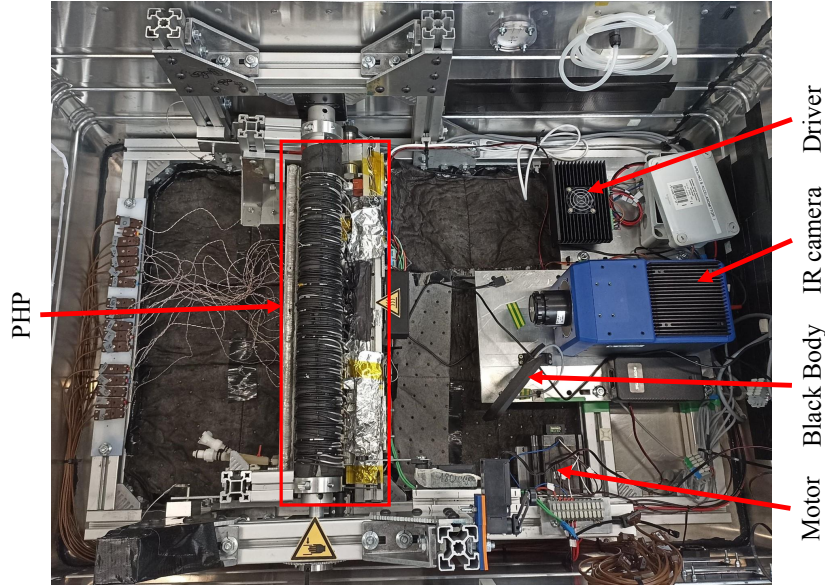


Figure 3.7: Overview of the Experimental Box.

The Deployable *PHP* under study features a capillary tube ($d_{\text{int}} = 1.6\text{mm}$, $d_{\text{ext}} = 2.6\text{mm}$), made of aluminium 6063 is shown in Figure 3.8. It is bent into a closed-loop serpentine with 11 U-turns in the evaporation section, resulting in 22 channels. The adiabatic, evaporator, and condenser sections are 715mm , 10mm , and 75mm long, respectively (Table 3.4). The *PHP* is shaped as a torsional spring in the adiabatic section, the coil diameter is 65mm , $N = 3.5$ coils per connection, totalling $L_{\text{coil}} = 715\text{mm}$ (90% of the channel length). The *PHP* is partially filled with *HFE – 7000* by Novec™, with a volumetric filling ratio of 70%. The *PHP* is mechanically connected

to the structure by multiple joints.

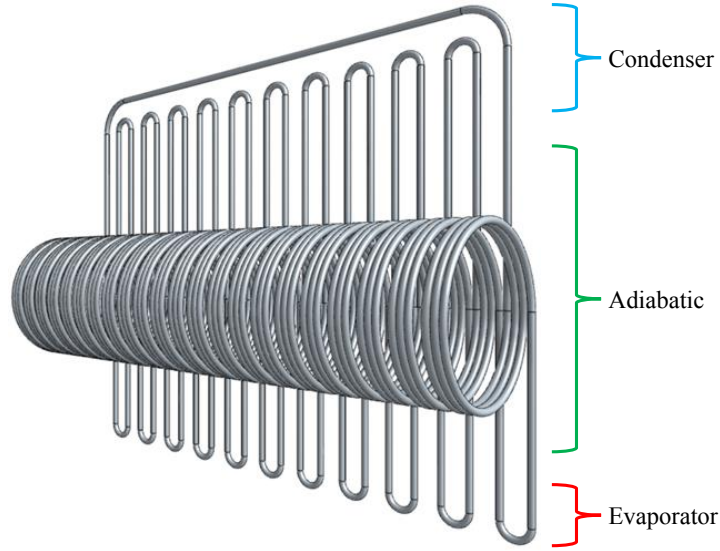


Figure 3.8: Deployable Pulsating Heat Pipe.

Table 3.4: PHP's geometry parameters.

Internal diameter	1.6	<i>mm</i>
External diameter	2.6	<i>mm</i>
Evaporator section length	10	<i>mm</i>
Condenser section length	75	<i>mm</i>
Adiabatic section length	715	<i>mm</i>

The thermal subsystem is divided into two main components: heater and cooler.

The heating section is designed to provide the necessary thermal power to the *PHP*'s evaporator. The evaporation section is enclosed between two aluminum heat spreaders, which are clamped to the tubes using screws (3.9. This section comprises three main components: the heater, the power supply, and the thermal switches. Heat is supplied by an ohmic heater, which is clamped onto the evaporator zone of the *PHP* and receives power from a

programmable DC power supply. A flat heater, 500mm in length (Joule Heater Hotspring[®]/Maxi - type WRP), connected to the spreaders provides the necessary heat input.

The cooling section is designed to extract heat from the *PHP*'s condenser section, maintaining a constant temperature. This process is facilitated by a cold plate connected to a liquid loop system. The condenser area is cooled by a loop circulating distilled water, with the loop's tubes inserted into a grooved aluminum plate that interfaces directly with the condenser section. The cooling fluid effectively transports heat from the condenser to the external environment, with heat dissipation enhanced by a thermoelectric cooling stage. This stage consists of two parallel banks of five Peltier cells each (totaling ten cells), coupled with a liquid cooling plate on one side and a pin-fin heat sink on the other. A variable-speed 12V gear pump regulates the circulation of the cooling fluid within the loop, which is contained within an umbilical pipe equipped with drip-free quick connectors, facilitating connections between the Experimental Box and the Control Rack.

The automation subsystem (described in the following sections) deploys the condenser section, while the evaporator remains fixed to the support structure.

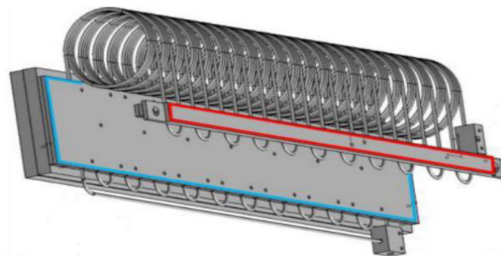


Figure 3.9: Deployable PHP. Heater in red, Cold plate in blue.

The automation subsystem is composed by a stepper motor (3Nm torque - Figure 3.10), a toothed belt drive, a controller and a power supply. The motor will change the *PHP* configuration by opening it and closing it by a 45° steps from a totally folded configuration, to a totally unfolded configuration.

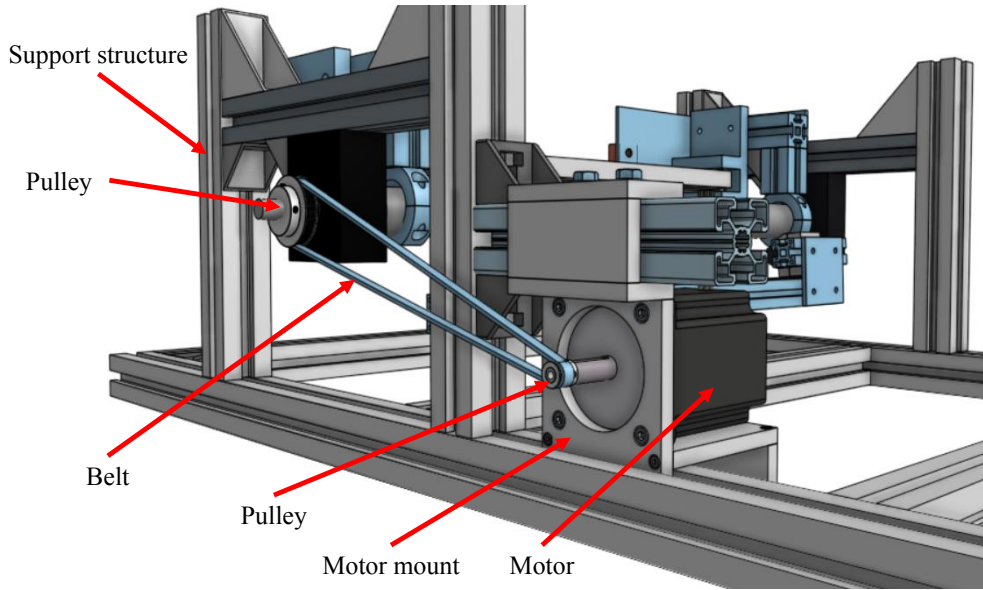


Figure 3.10: Motor and transmission.

Figure 3.11 shows the 5 static working positions of the *PHP*: the condenser section (*blue*) rotates starting parallel to the evaporator section (*red*) and pointing toward the ground and ends its movement when it is placed vertically above the evaporator section.

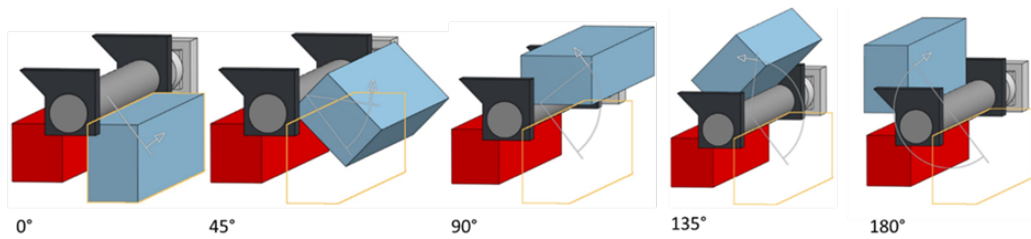


Figure 3.11: PHP working positions.

The data acquisition subsystem is used to gather experimental measurements of temperature and pressure. It is composed of an IR Camera, 15 T-Type thermocouples connected to the external surface of the *PHP*, and 2 pressure transducers (Keller[®] 33X) inserted in two T-junctions at the ends of the same pipe. The sensors can be located as shown in Figure 3.12, following the same configuration used previously by Perna et al., 2024.

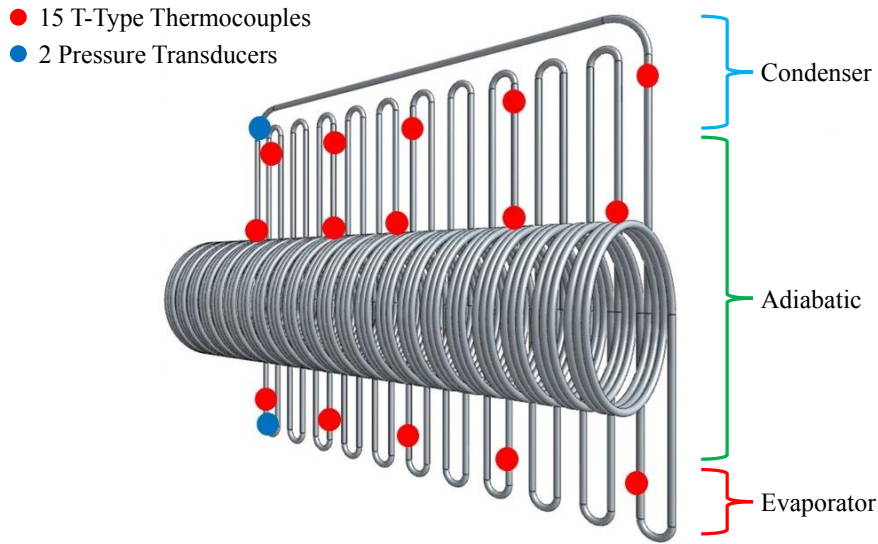


Figure 3.12: Sensors distribution on PHP.

The thermocouples are glued to the evaporator, adiabatic and condenser section external surfaces, 5 for each section. The pressure transducers are connected to two respective T-junction inserted on the *PHP*, at the evaporator and condenser section of the same tube. The IR Camera (Flir SC7000) is placed in front of the *PHP*'s evaporator section, at 254 *mm* of distance.

The device captures images at a 25 *Hz* frequency, focusing on five pipes in direct contact with the evaporator section (60 *mm* height). The recording zone of the Camera is a portion of six consecutive pipes, as shown in Figure

3.13. Since radiative properties of surfaces are a key requirement for accurate thermal imaging and aluminium typically is a low-emissivity material, the framed tubes are painted with an opaque black paint. This foresight allows to increase and uniform the emissivity of the surface of the pipes.

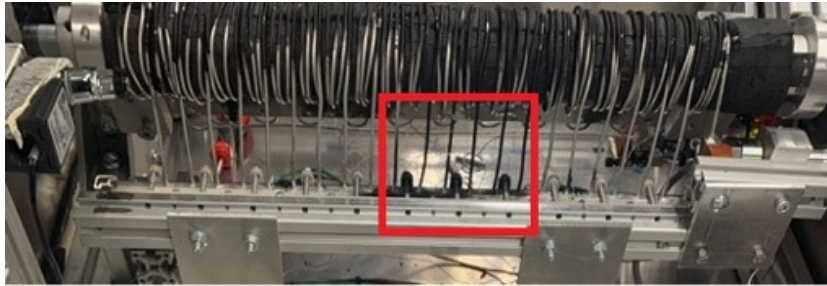


Figure 3.13: IR Camera recording zone.

3.3.1.2 Control Rack

The Control Rack (Figure 3.14), is needed for monitoring and controlling the experiment and hosts power supplies, part of the cooling loop system and 2 laptops for managing all the subsystems.



Figure 3.14: Overview of the Control Rack.

As shown in Figure 3.15, two operators will manage the experiment via the Control Rack. The Control Rack has been designed to allow the operators full control of the experiment without the need to leave their workstation.

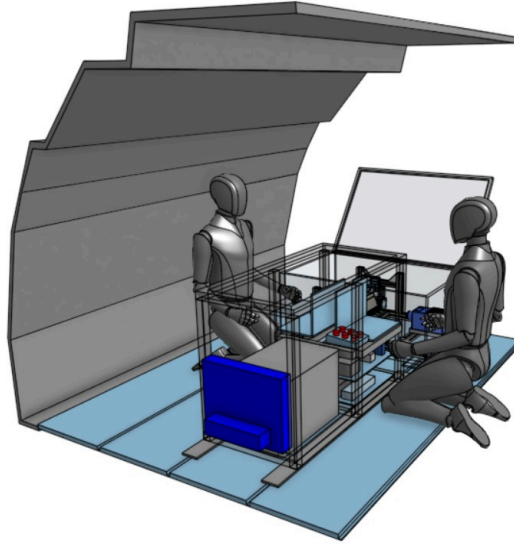


Figure 3.15: Flight position of the two operators.

The Control Rack contains the power supplies, a part of the cooling loop, as well as the devices for managing and monitoring the experiment. Specifically, there are two laptops: the first one is dedicated to data acquisition from the IR Camera, while the second one collects data from the cRIO[®] (National Instrument), to which thermocouples and pressure transducers are connected. Additionally, there are two physical control panels to operate the movement of both the *PHP* and the blackbody. This setup allowed the experiment to be managed during the in-flight test campaign without the need to directly access the interior of the Experimental Box.

Given the presence of more than 0.5 liters of liquid, the experiment required two levels of containment (Novespace, 2022). The first level is provided

by appropriate hydraulic connections for the liquid loop system. The second level of containment is achieved through the liquid loop enclosure, consisting of Lexan panels sealed inside the control rack. For connection to the Experiment Box, an umbilical conduit containing silicone tubing was used.

3.3.2 Data Collection

3.3.2.1 IR Data

Concerning data acquisition by IR Camera, the recording zone, the flight procedures and the data synchronization method will be exposed in this section.

As shown in Figure 3.16, this arrangement allowed for the registration of six tubes in the adiabatic zone adjacent to the evaporator using the thermal camera. With this layout, each detected pixel corresponds to a dimension of $0.182mm$, and the diameter of each tube is defined as 14 pixels.

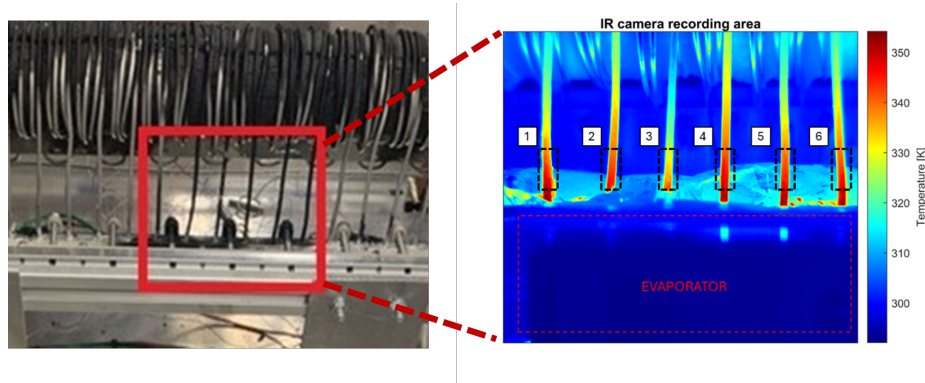


Figure 3.16: IR Camera recording area.

The IR Camera calibration procedure is performed at the beginning of the flight (about 10 minutes after the IR Camera is turned on) and repeated during each pause between parabolas sets (every 15 minutes) to maintain high accuracy of the device. For the calibration procedure, a motorized black body is employed to cover the IR Camera during the calibration process. Once the black body is covering the camera lens, the calibration procedure is started through the software Altair. After its completion, the black body is

removed to resume data acquisition activities. In addition to the calibration procedure, the overall flight procedure, reported near the dedicated IR Camera laptop in the Control Rack, including the initial startup and individual acquisitions, is also shown in the Figure 3.56. The acquisition time of each IR Camera record was set at 60 seconds. Given an acquisition frequency of $25Hz$, each record will contain exactly 1500 frames.

In Figure 3.17, next to the IR Camera, the blackbody used for the calibration procedure is visible. This blackbody was *taylor-made* for this specific application and produced using 3D Printing with black *PLA*.

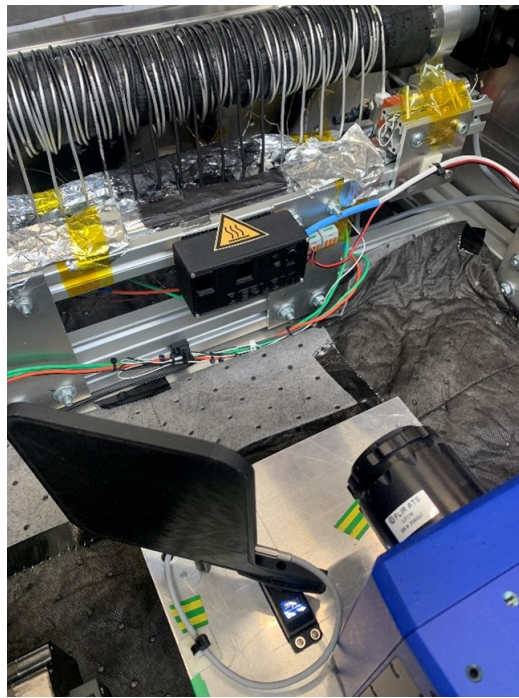


Figure 3.17: IR Subsystem.

The choice of this material, combined with the surface roughness achieved by printing on a textured plate and the automation of its positioning, enabled precise and reliable calibrations. During the calibration process, the

blackbody must be placed externally to the lens and angled to avoid reflections (Figure 3.18-3.19). This setup allows for the calibration procedure and the evaluation of residual noise with the blackbody positioned in front. If the recorded standard deviation is less than the value of background noise, the calibration is deemed successful.

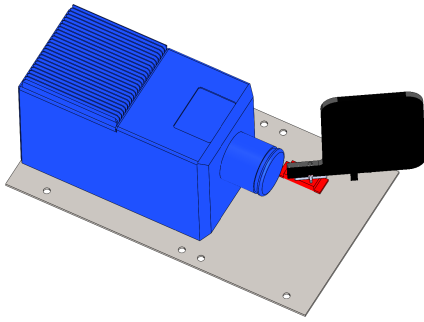


Figure 3.18: Blackbody in recording position.

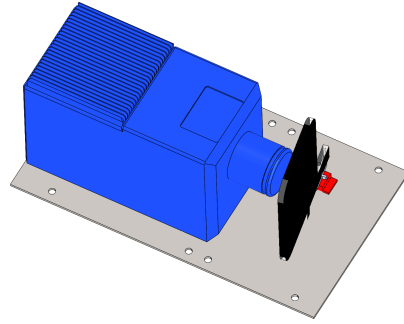


Figure 3.19: Blackbody in calibration position.

To ensure both accuracy and reliability of the acquisition system with the IR Camera, a procedure was implemented to record each parabola separately, as previously described. Additionally, *visual* triggers were placed in the recording zone, enabling precise identification of the hypergravity and microgravity phases during post-processing. The synchronization of each recording with microgravity intervals is done *visually* (in the data acquisition software related to the IR Camera); made using two resistors ($330\,\Omega$), which serve as *visual feedback* for the operational conditions. The triggers are installed on a custom *PCB* in an IP2X enclosure (Figure 3.20), and powered by Arduino MEGA[®], to which an accelerometer (MPU6050) is also connected.

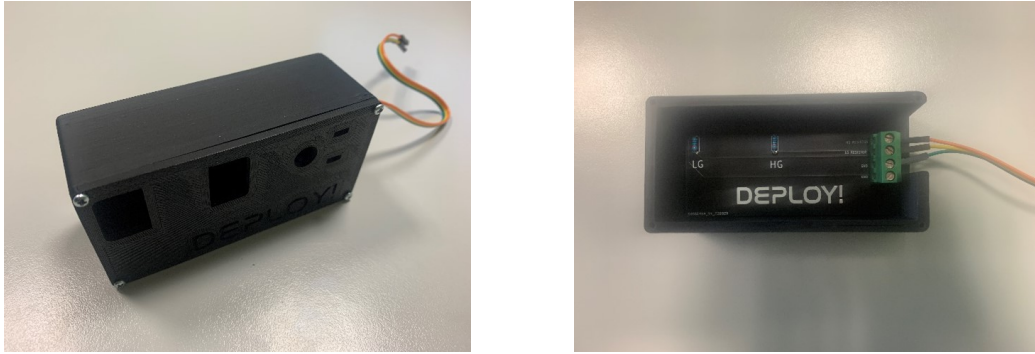


Figure 3.20: In the image on the left, the case for the *PCB* with IP2X specifications can be seen, while on the right, the assembled *PCB* is shown.

- i. When the accelerometer measures an acceleration value $> 1.3\,g$, the right resistor (*HG*) will switch on.
- ii. When the accelerometer measures an acceleration value $< 0.3\,g$, the left resistor (*LG*) will switch on.

The mounting of the case in the recording zone of the IR Camera inside the Experimental Box is shown in Figure 3.17.

During hypergravity, the dedicated resistor will switch on, and during microgravity, the dedicated resistor will switch on. Their change in temperature will be recorded by the IR Camera and serve as visual feedback of gravity conditions.

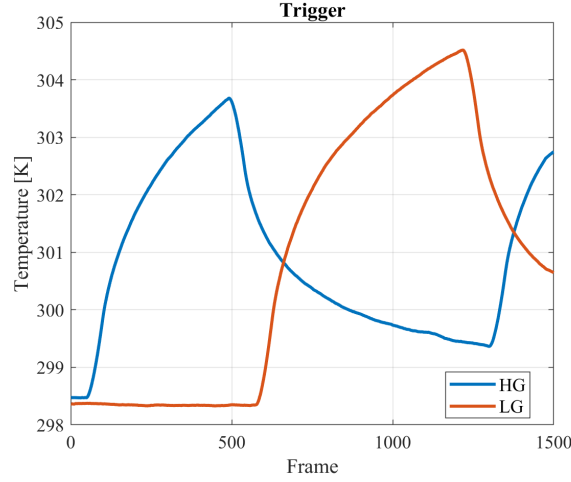


Figure 3.21: Trigger temperature trend during a parabola - filtered data.

As shown in the Figure 3.21, the graph displays the temperature trends of the resistors functioning as triggers.

Specifically, related to this last Figure, the onset of the hypergravity phase (HG) is indicated by the point where the derivative of the blue curve, $f(x)$, becomes positive. Conversely, the end of the hypergravity phase is marked by the derivative of the blue curve becoming negative. Similarly, the microgravity (LG) interval can be defined by performing the same analysis on the orange curve, $g(x)$. Additionally, the transition phase between hypergravity and microgravity can be observed when the derivative of the blue curve is negative while the derivative of the orange curve is zero. For completeness, the following Table 3.5 summarizes the previously described phases, listed in the order of occurrence as shown in the Figure 3.21.

In addition to the two triggers, the device includes an IR-LED, which is manually controlled by the PC and linked to the cRIO[®]. This trigger generates a square wave inside the cRIO[®], that corresponds to the *on/off*

Table 3.5: Summary of phase identification based on the triggers values.

Phase	Condition
Hypergravity (<i>HG</i>)	$f'(x) > 0$
Transition Phase	$f'(x) < 0 \wedge g'(x) = 0$
Microgravity (<i>LG</i>)	$g'(x) > 0$

state of the IR-LED, enabling semi-automatic synchronization between the two distinct acquisition systems. Figure 3.22 shows the positions of the three visual triggers within the recording zone of the IR Camera: orange denotes microgravity, blue indicates hypergravity, and red represents the square wave generator used for synchronization with the cRIO[®].

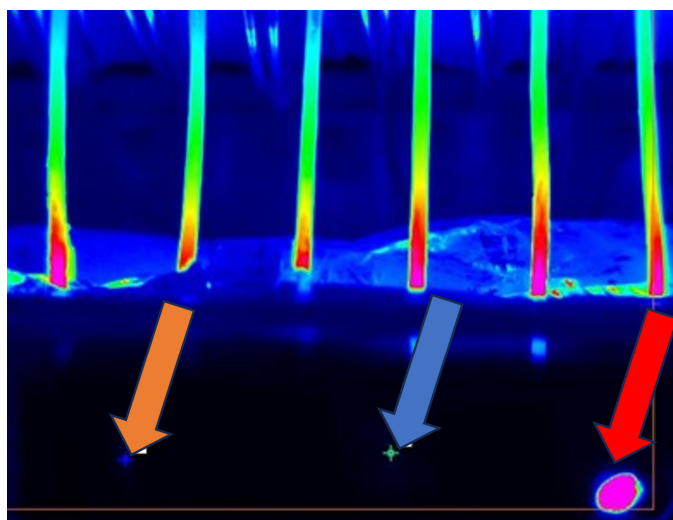


Figure 3.22: Visual trigger during post-processing phase.

3.3.2.2 cRIO Data

This second data acquisition system will interface with a laptop via an Ethernet connection to the NI[®] cRIO-9068 controller. Measurements will be acquired in *real-time* through a LabView[®] interface and stored as text files on the laptop. The thermocouples used are T-type models from RS Pro[®], with the exception of two K-type thermocouples installed in the thermal switch for monitoring purposes. The pressure sensors employed are the Keller[®] 33X model, featuring a measurement accuracy of $\pm 0.05\%$ of the full-scale range, where the range spans from 0 to 3 bar. In addition, an accelerometer will be employed to accurately monitor and define microgravity phases.

The cRIO[®] system, provided by NI[®], model 9074, serves as a central hub for all signals. Inside the chassis, module 9213 for thermocouples and module 9205 for pressure signals are installed. Communication between the cRIO[®] and a laptop is established via Ethernet. A LabView[®] interface facilitates data reading and collection from the cRIO[®]. The instrument itself is designed to autonomously organize and post-process the collected data. This feature is crucial in mitigating the risk of data loss or communication noise, even in cases where the PC is compromised or there are issues with the connection. The cRIO[®]'s independent data storage capability ensures the integrity of the data acquisition process.

This second data acquisition system is significantly less complex than the previous one. Once data recording is initiated via LabView[®], the operator's primary tasks are to monitor the parameters and operate the *PHP* in accordance with the test matrices outlined in the following pages.

The pressure signal cables are shielded, and the shields are grounded to the cRIO[®]'s ground to eliminate any noise caused by electrical or magnetic interference. The thermocouples are connected to the cRIO[®] via junctions located in the test area, all of which are provided by RS-Pro[®]. Although the thermocouple cables are unshielded, they are positioned at least 50 *mm* away from any power cables to reduce potential interference. Temperature data is acquired at a frequency of 50 *Hz*, while pressure signals are sampled at a higher rate of 2000 *Hz*. The cRIO[®] averages every 20 samples to achieve an effective acquisition frequency of 100 *Hz*.

3.3.2.3 Parabolic flight test session

The *PFC* test sessions followed a strict procedure to ensure compliance with the technical and safety requirements of the operational environment. Each experiment, including the assembly of the system onboard the aircraft, was powered on only after takeoff and deactivated before the landing maneuver (Novespace, 2022). The first series of parabolic manoeuvres, consisting of five parabolas, began approximately 30 minutes after take-off.

The parabolic flight was divided into six groups of maneuvers, and the experiment was tested in five different configurations, with one group of parabolic maneuvers reserved as a backup attempt. This planning ensured the effectiveness of the test and the collection of the necessary data for analysis.

On the first and second days, the tests closely mirrored the static tests conducted during ground testing.

On the first flight day, the system was activated with the evaporator's input heating power set to 56 *W* and the condenser temperature maintained at 25°C (Table 3.6). The initial configuration of the *PHP* was folded at 0°. Each series of parabolas corresponded to a different testing configuration: the first series involved the *PHP* at 0°, the second at 45°, followed by 90°, 135°, 180°, and the final series was dedicated to the 0° configuration for redundancy, as shown in Figure 3.23.

On the second flight day, the *PHP* was tested with a heating power input of 34 *W* and a fixed condenser temperature of 20°C (Table 3.7). The *PHP* was evaluated in three unfolding configurations: 0°, 90°, and 180°, as

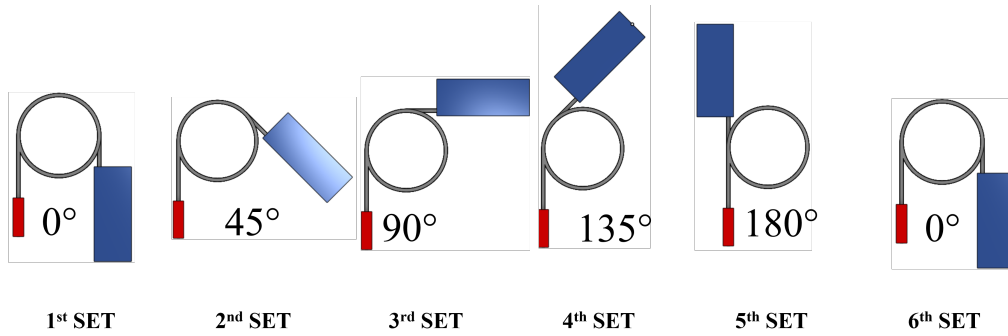


Figure 3.23: PFC Day 1: static test configuration.

shown in Figure 3.24. The first set of parabolas was excluded to allow the *PHP* to reach steady-state conditions. The second set was conducted at 0° , followed by unfolding the device to 90° during the microgravity interval of the 11^{th} parabola, with testing in this configuration during the third set. This procedure was repeated during the 16^{th} parabola. At the 21^{th} parabola, the *PHP* was unfolded back from 180° to 90° , and at the 26^{th} parabola, it was returned to the initial 0° configuration. This test session was successful, with data collected from all 30 parabolas, including the first five *non-steady-state* parabolas.

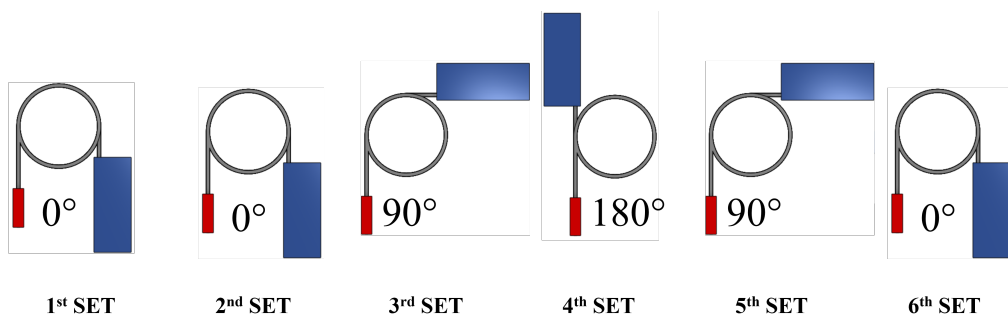


Figure 3.24: PFC Day 2: static test configuration.

On the third flight day, the *PHP* was tested both in steady-state and dynamic unfolding conditions. The initial thermal boundary conditions were

34 W of input heating power and a fixed condenser temperature of 30°C (Table 3.8). The first set of parabolas allowed the *PHP* to reach steady-state conditions. The second set focused on evaluating the performance of the device in the 0° unfolding configuration. During the microgravity interval of the 11th parabola, the *PHP* was unfolded to 180° and observed during the third set of parabolas. During mid-flight breaks and the subsequent two sets of parabolas, the dynamic movement of unfolding and folding were tested in both microgravity and normal gravity (Figure 3.25). This provided insights into the behavior of the *PHP* during configuration changes in different gravitational conditions.

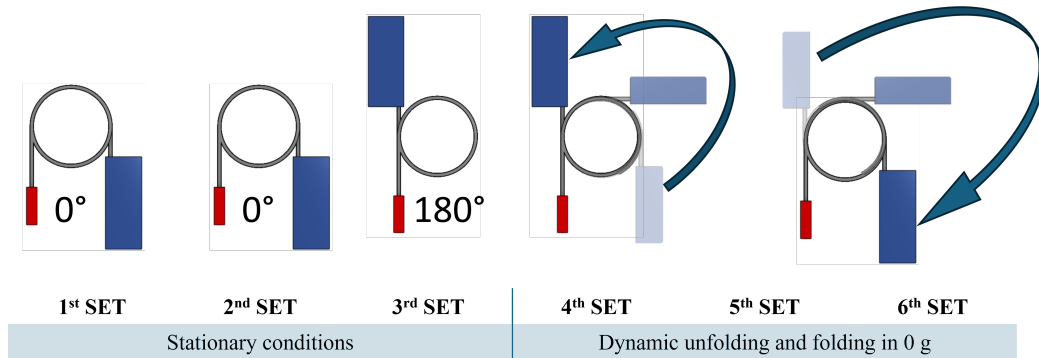


Figure 3.25: PFC Day 3: dynamic test configuration.

However, between the fifth and sixth groups of parabolas, a failure occurred in the torque transmission mechanism, resulting in the disassembly of the joint between the stepper motor shaft and the small pulley. This failure was irreparable, causing the *PHP* to remain locked in the 0° configuration. Following this issue, the power input level was increased to 56 W , and during the last set of parabolas, the behavior of the *PHP* was observed during the transition to the new power input level. Comparing the first and last sets of

parabolas provided a comprehensive understanding the transitional working conditions, bringing the total count of useful data collected to encompass the entire flight.

Table 3.6: 83th ESA PFC Day 1 DEPLOY! Test-Matrix.

Parabola	Angle [°]	Power [W]	T_{Cond} [°C]	Notes
0	0	56	25	<i>Not Steady-state</i>
1	0	56	25	<i>Not Steady-state</i>
2	0	56	25	<i>Not Steady-state</i>
3	0	56	25	<i>Not Steady-state</i>
4	0	56	25	<i>Not Steady-state</i>
5	0	56	25	<i>Not Steady-state</i>
<i>Pause 1</i>				<i>Calibration</i>
6	0 → 45	56	25	—
7	45	56	25	—
8	45	56	25	—
9	45	56	25	—
10	45	56	25	<i>Not recorded</i>
<i>Pause 2</i>				<i>Calibration</i>
11	45 → 90	56	25	< 90
12	90	56	25	< 90
13	90	56	25	< 90
14	90	56	25	<i>TC problem</i>
15	90	56	25	<i>Not recorded</i>
<i>Pause 3</i>				<i>Calibration</i>
16	90 → 135	56	25	—
17	135	56	25	—
18	135	56	25	—
19	135	56	25	—
20	135	56	25	—
<i>Pause 4</i>				<i>Calibration</i>
21	135 → 180	56	25	—
22	180	56	25	—
23	180	56	25	—
24	180	56	25	—
25	180	56	25	—
<i>Pause 5</i>				<i>Calibration</i>
26	180 → 0	56	25	—
27	0	56	25	—
28	0	56	25	<i>Power cutoff</i>
29	0	56	25	<i>Power cutoff</i>
30	0	56	25	<i>Power cutoff</i>

Table 3.7: 83th ESA PFC Day 2 DEPLOY! Test-Matrix.

Parabola	Angle [°]	Power [W]	T_{Cond} [°C]	Notes
0	0	34	20	<i>Not Steady-state</i>
1	0	34	20	<i>Not Steady-state</i>
2	0	34	20	<i>Not Steady-state</i>
3	0	34	20	<i>Not Steady-state</i>
4	0	34	20	<i>Not Steady-state</i>
5	0	34	20	<i>Not Steady-state</i>
<i>Pause 1</i>				<i>Calibration</i>
6	0	34	20	—
7	0	34	20	—
8	0	34	20	—
9	0	34	20	—
10	0	34	20	—
<i>Pause 2</i>				<i>Calibration</i>
11	0 → 90	34	20	—
12	90	34	20	—
13	90	34	20	—
14	90	34	20	—
15	90	34	20	—
<i>Pause 3</i>				<i>Calibration</i>
16	90 → 180	34	20	—
17	180	34	20	—
18	180	34	20	—
19	180	34	20	—
20	180	34	20	—
<i>Pause 4</i>				<i>Calibration</i>
21	180 → 90	34	20	—
22	90	34	20	—
23	90	34	20	—
24	90	34	20	—
25	90	34	20	—
<i>Pause 5</i>				<i>Calibration</i>
26	90 → 0	34	20	—
27	0	34	20	—
28	0	34	20	—
29	0	34	20	—
30	0	34	20	—

Table 3.8: 83th ESA PFC Day 3 DEPLOY! Test-Matrix.

Parabola	Angle [°]	Power [W]	T_{Cond} [°C]	Notes
0	0	34	25	<i>Not Steady-state</i>
1	0	34	25	<i>Not Steady-state</i>
2	0	34	25	<i>Not Steady-state</i>
3	0	34	25	<i>Not Steady-state</i>
4	0	34	25	<i>Not Steady-state</i>
5	0	34	25	<i>Not Steady-state</i>
<i>Pause 1</i>				<i>Calibration</i>
6	0	34	25	—
7	0	34	25	—
8	0	34	25	—
9	0	34	25	—
10	0	34	25	<i>Not recorded</i>
<i>Pause 2</i>				<i>Calibration</i>
11	0 → 180	34	25	—
12	180	34	25	—
13	180	34	25	—
14	180	34	25	—
15	180	34	25	—
<i>Pause 3</i>				<i>Calibration</i>
16	0 → 180	34	25	—
17	180	34	25	—
18	180 → 0	34	25	—
19	0	34	25	—
20	0 → 180	34	25	—
<i>Pause 4</i>				<i>Calibration</i>
21	0 → 180	34	25	—
22	180	34	25	—
23	180 → 0	34	25	—
24	0	34	25	—
25	0 → 180	34	25	<i>Pulley failure</i>
<i>Pause 5</i>				<i>Calibration</i>
26	0 → 180	56	25	0
27	180	56	25	0
28	180 → 0	56	25	0
29	0	56	25	0
30	0 → 180	56	25	0

3.3.3 Data Post-Processing

The primary objective of this case study was to prepare the experiment, execute the test campaign, and collect data systematically to ensure that it is suitable for future analysis.

For completeness, this section presents the preliminary and partial results obtained from the IR Camera acquisitions. Although preliminary, these results are essential to validate the experiment and establish a framework for future studies centered on these data.

In the first part of the analysis, the results obtained from static tests conducted with the device positioned in angular configurations of 0° , 90° and 180° are presented.

The second part of this preliminary analysis focuses on the dynamic openings and closures of the device.

The IR recordings are pre-processed to extract a rectangular pixel section (about 20 pixels in width and 40 pixels in height) for each tube near the evaporator in the adiabatic section.

Further processing takes place in a tailor made script, transforming records into *n-dimensional* matrices, with *n* corresponding to a single frame. Once these matrices are created, by visualizing the temperature trends of the visual triggers, it becomes possible to extract data for microgravity, hypergravity and normal-Earth gravity conditions. This allows for a comparison of the behavior of the *PHP* under microgravity, hypergravity, and normal-Earth gravity conditions with the same power and working angle.

3.3.3.1 Static test

Figure 3.26 shows the plot of the maximum detected temperature in the observed section of pipe $n^{\circ}6$ (numbered in Figure 3.16), for three different static positions (0° , 90° , and 180°), comparing microgravity, hypergravity, and normal-Earth gravity.

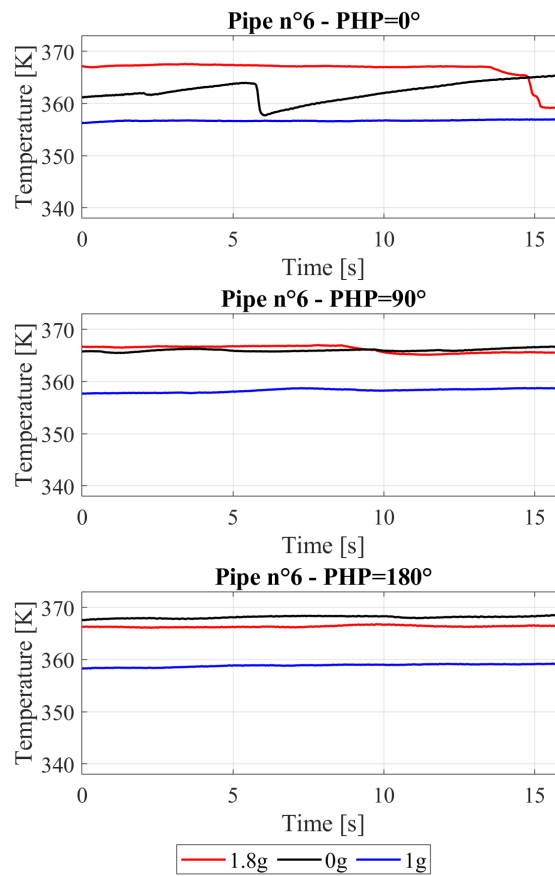


Figure 3.26: Maximum temperature recorded for Pipe $n^{\circ}6$ under three gravity levels.

For the hypergravity and microgravity phases, data from parabolas $n^{\circ}27$, 13, and 24 of the first day were utilized (Table 3.6). For the initial analysis, a

16-second time window was utilized within the microgravity phase to mitigate edge effects at the beginning and end of the period. This approach was adopted to ensure a detailed examination of the behavior specifically during the microgravity phase.

It is important to note that parabola $n^{\circ}13$ was included despite not having an opening precisely at 90° . This decision was made due to the challenges and the unique nature of the test, with the goal of achieving the most comprehensive overall assessment possible. In these first plots, the *blue* curve represent the maximum temperature under normal-Earth gravity. It can be observed that for the Earth gravity condition, there is no significant difference in the behavior of the device in the three tested static positions. In contrast, the same observations under hypergravity and microgravity conditions show temperature drops occurring in the observed section of the *PHP* when in a closed configuration, 0° (first subplot, *red* and *black* curves respectively).

For the sake of completeness, the post-flight acceleration data provided by Novespace for these parabolas are presented to verify the accuracy and quality of the microgravity and hypergravity conditions generated inside the Air Zero G (Figure 3.27-3.28-3.29). These images depict the aircraft's executed trajectory in black, while the acceleration values along the three axes are represented in blue, red, and green, respectively.

Specifically, for this analysis, the values recorded in microgravity were analyzed in addition to the values in hypergravity recorded in the ascending phase of the parabolas. Regarding the data collected under normal-Earth gravity, these were recorded during the days preceding the flight in the ground testing phase. The same power level and condenser temperature as those used

on the flight day were employed. Additionally, the boundary conditions were consistent with those of the flight, as the ground test was conducted aboard the Air Zero-G aircraft.

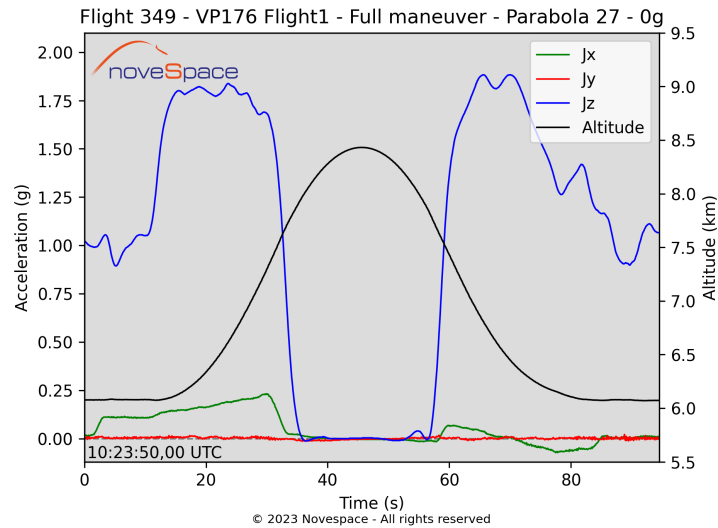


Figure 3.27: Post-Flight acceleration data from Novespace (Day 1, Parabola n° 27).

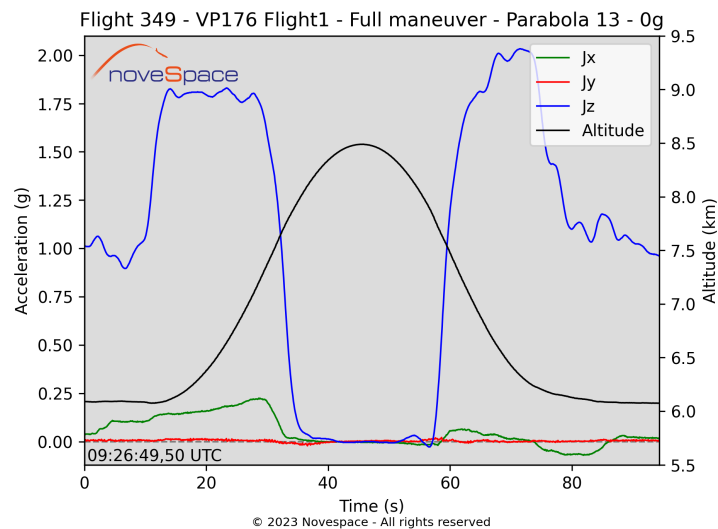


Figure 3.28: Post-Flight acceleration data from Novespace (Day 1, Parabola n° 13).

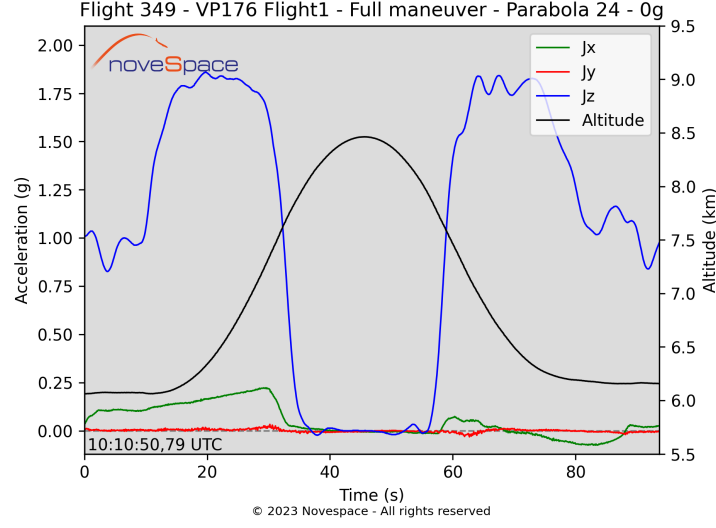


Figure 3.29: Post-Flight acceleration data from Novespace (Day 1, Parabola n° 24).

Based on the work of Pagliarini et al., 2021b, the thermographic observation data is processed through the procedure described below to extract an estimation of the local heat fluxes for the observed sections of the *PHP* tubes. The observed sections can be approximated as 1D elements, assuming a negligible temperature gradient along the tube circular section.

In this preliminary analysis, the thin wall assumption, $\frac{t}{r} \ll 1$, (Pagliarini et al., 2021a), has been applied for the 0.5mm pipe wall thickness as shown in Figure 3.30).

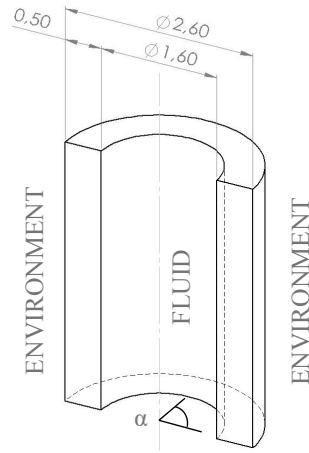


Figure 3.30: Sketch of a single pipe.

Given this geometry, a resulting 2D-axisymmetric domain is obtained by assuming that the temperature gradient is nearly negligible along the angle α . Moreover, a spot analysis was performed and, as a result, the spatial derivative (Figure 3.31), along the axis of the pipe was neglected.

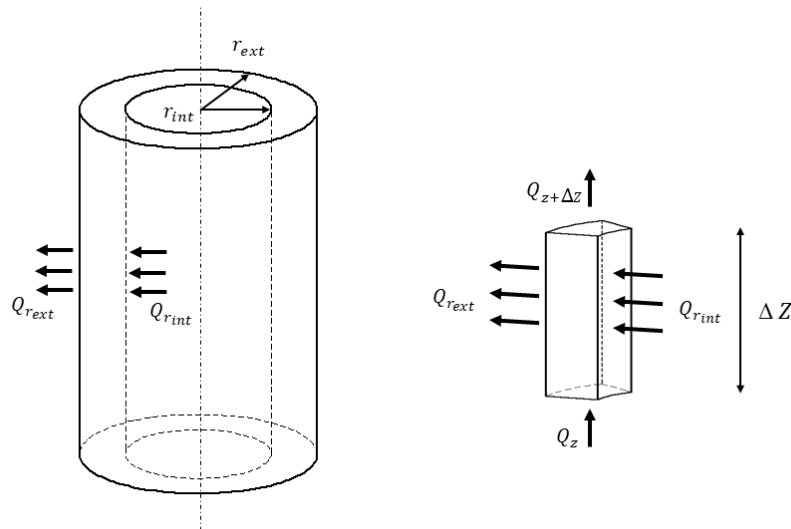


Figure 3.31: Portion of the pipe (left) and generic wall element (right).

The heat flux at the inner surface of the observed pipe wall is calculated using Equation 3.4 from Pagliarini et al., 2021b, where the term $k \cdot \frac{\partial^2 T}{\partial z^2}$ is omitted because of the previously illustrated assumption of spot analysis.

$$q = \frac{\left(\rho c_p \frac{\partial T}{\partial t} \cdot (r_{\text{ext}}^2 - r_{\text{int}}^2) + \frac{T - T_{\text{env}}}{R_{\text{env}}} \cdot 2r_{\text{ext}} \right)}{2r_{\text{int}}} \quad (3.4)$$

Where ρ and c_p are the density and the specific heat of the *PHP* wall material (Aluminium 6063), T is the temperature detected by the IR Camera, r_{ext} and r_{int} are the pipe's external and internal wall radiuses, T_{env} and R_{env} are the environmental temperature (detected by thermocouples) and environmental thermal resistance, respectively. The environmental thermal resistance value is assumed to be equal to $0.1 (m^2 K)/W$ (Pagliarini et al., 2021a) and fixed (reasonable variations in R_{env} are negligible in the calculation). A positive value of heat flux is associated with the heat transfer from the fluid to the tube wall, while a negative value indicates the opposite transfer direction.

The second part of the static analysis is performed on three selected pipes: $n^\circ 2, 4$, and 6 , in the 0° (closed) configuration, for which the temperature plots show significant drops in temperature within the observed time interval. The results are presented as the previous analysis, in three different plots, each showing the heat flux value over time when the *PHP* is subjected to different gravity levels: microgravity, hypergravity, and normal-Earth gravity, and shown in Figure 3.32. In these plots, drops can be noted in the graphs under hypergravity and microgravity conditions; while they are missing under normal-Earth gravity conditions.

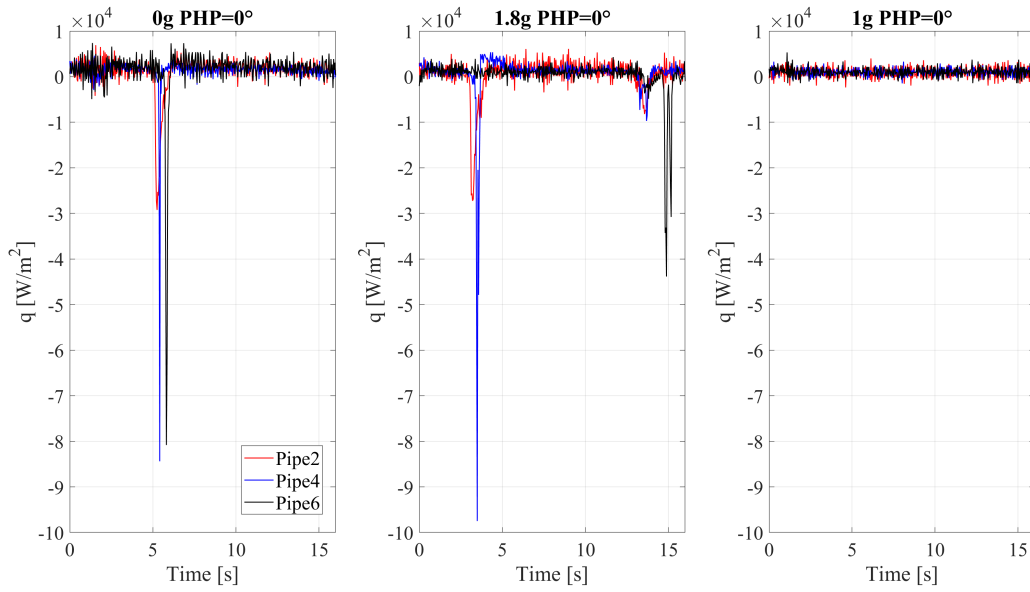


Figure 3.32: Heat flux between the fluid and the wall under different gravity conditions.

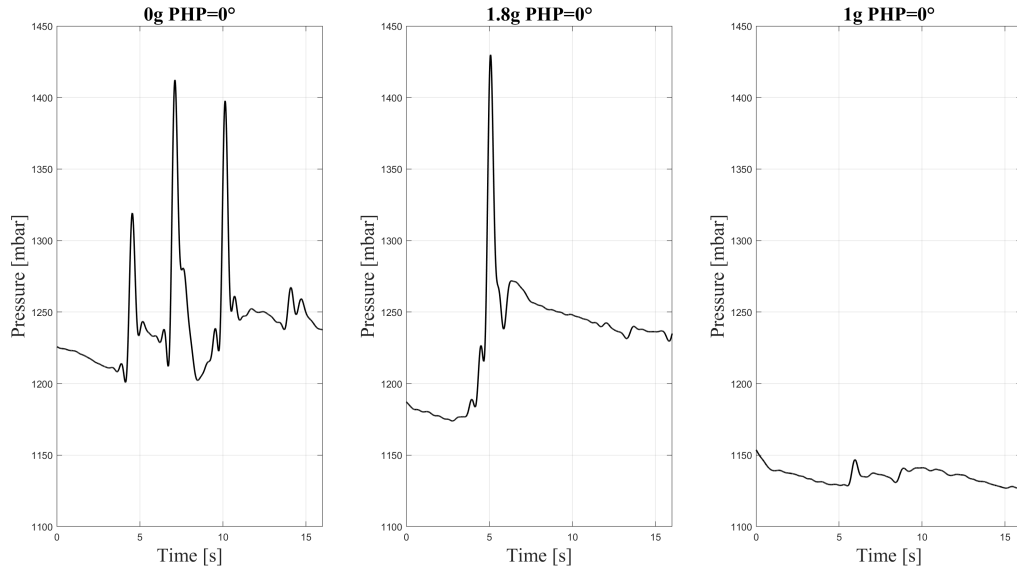


Figure 3.33: Evaporator pressure values under different gravity conditions.

Figure 3.33 shows data from the pressure sensor located at the evaporator

section (Figure 3.12). Moving from left to right across the graphs, the first graph reveals 3 pressure peak in the microgravity phase. In the second graph, recorded under hypergravity conditions, only one pressure spike is recorded. In contrast, the third graph, representing the data under normal-Earth gravity conditions, shows the absence of pressure peaks.

These observations confirm the results of radiometric analysis, as a drop in temperature is associated with a pressure spike, indicating a significant evaporative phenomenon. Evaporation leads to a decrease in temperature, as the process removes heat from the system due to the phase change of the fluid mass. This, in turn, generates an increase in pressure, which results in an isolated *start-up* (process of starting and activating the device to initiate heat transfer), of the device. However, complete system activation is not observed due to the limited power levels available during the experimental campaign.

Qualitatively, it can be observed that the variation in gravity levels seems to promote the *start-up* of the *PHP*. Specifically, the heat flux experiences a significant drop in both microgravity and hypergravity conditions, but not in normal-Earth gravity. However, the heat input at the evaporator is not sufficient for the *PHP* to maintain such activations and achieve a pseudo-steady-state working condition, as evidenced by the return to low heat flux values following the described peaks.

3.3.3.2 Dynamic test

This section will present the results for the third day of flight, i.e., the tests of dynamic unfolding (Figure 3.34), and folding (Figure 3.35) of the device under microgravity conditions.

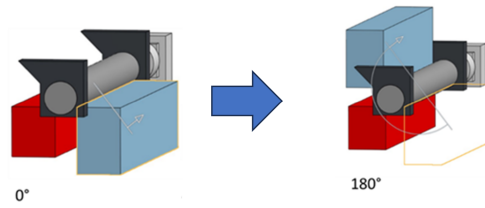


Figure 3.34: Dynamic unfolding movement of PHP.

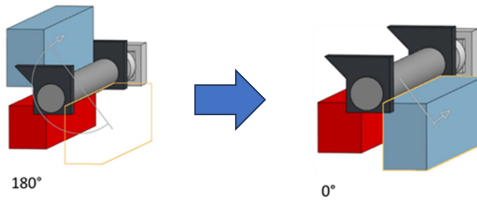


Figure 3.35: Dynamic folding movement of PHP.

Figure 3.36 shows the plot of the maximum detected temperature in the observed sections of pipes $n^{\circ}2$, 4, and 6 (Figure 3.16) during the dynamic opening and closing phases in microgravity. The data were recorded on the third day of the experimental campaign (Table 3.8), specifically from parabolas $n^{\circ}11$ and 18. In contrast to the static analyses, the current discussion presents graphs with a time interval of 20 seconds. This choice was made to encompass a broader range of data both before and after the microgravity phase, thereby providing a more comprehensive view of the observed behavior.

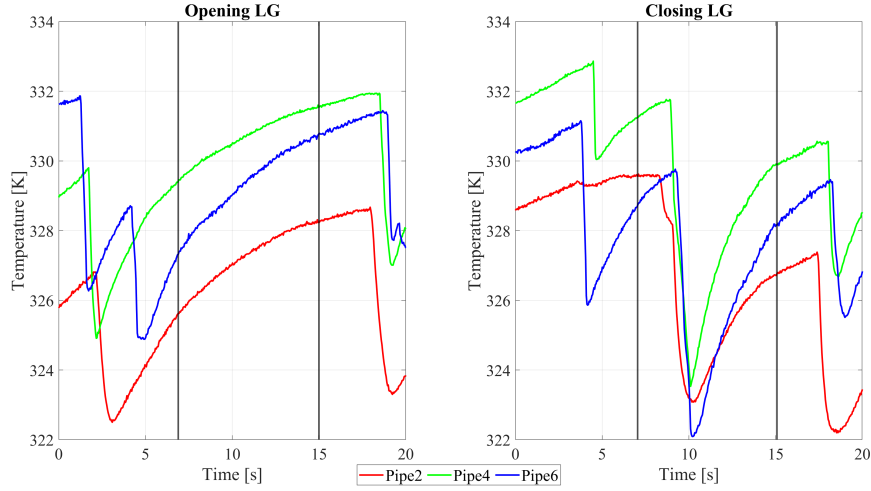


Figure 3.36: Maximum temperature recorded for Pipes $n^{\circ} 2 - 4 - 6$ during unfolding and folding movement in microgravity.

The two plots show only the temperature profiles recorded in microgravity, the plot on the left shows the unfolding data, while the right one shows the folding data. Additionally, the two black vertical lines represent the start and end of the dynamic opening or closing phase of the device. The 1D heat maps for all six pipes recorded for the parabolas analyzed in this section are given in the Appendix of this Chapter.

As observed in the graphs corresponding to the two analyzed parabolas, the opening and closing phases exhibit distinct behaviors in the *PHP* under microgravity conditions. In particular, temperature drops are noted before and after the opening phase, which seem to decrease during the dynamic phase. Conversely, temperature drops before and after the dynamic phase are also recorded in the closure phase; however, unlike the opening phase, these temperature drops become more pronounced during the dynamic phase.

Given the novelty and uniqueness of this type of test, it is crucial to

emphasize that the observed behaviors are not sufficient to draw firm conclusions. The results are based only on the parabolas analyzed and may not be representative of all operating conditions. One potential explanation for this behavior could be found in the inertial components resulting from the opening and closing dynamics of the device. These inertial phenomena could have introduced imbalances within the system, disturbing the internal dynamics of the device generated by capillary forces only and contributing to the manifestation of the observed phenomena.

Figure 3.37 shows the temperature profiles for tubes $n^\circ 2$, 4, and 6 under normal-Earth gravity conditions. These data were recorded during pause $n^\circ 4$ on the third day of testing. Notably, during the closing phase of the device in normal-Earth gravity, there are no significant temperature drops or spikes. Instead, the temperature exhibits a slightly increasing trend, which appears to be only minimally affected by the dynamic behavior of the system.

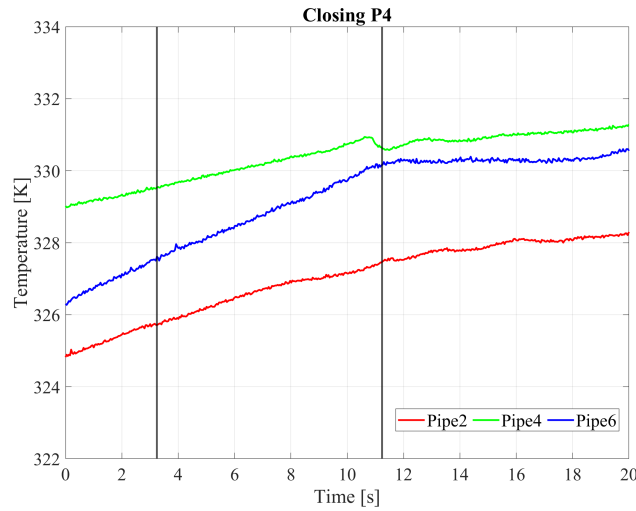


Figure 3.37: Maximum temperature recorded for Pipes $n^\circ 2 - 4 - 6$ during Day 3 Pause $n^\circ 4$.

For the sake of completeness, the post-flight acceleration data provided by Novespace for these parabolas are presented to verify the accuracy and quality of the microgravity and hypergravity conditions generated aboard the Air Zero G (Figure 3.38-3.39). These images depict the aircraft's executed trajectory in black, while the acceleration values along the three axes are represented in blue, red, and green, respectively.

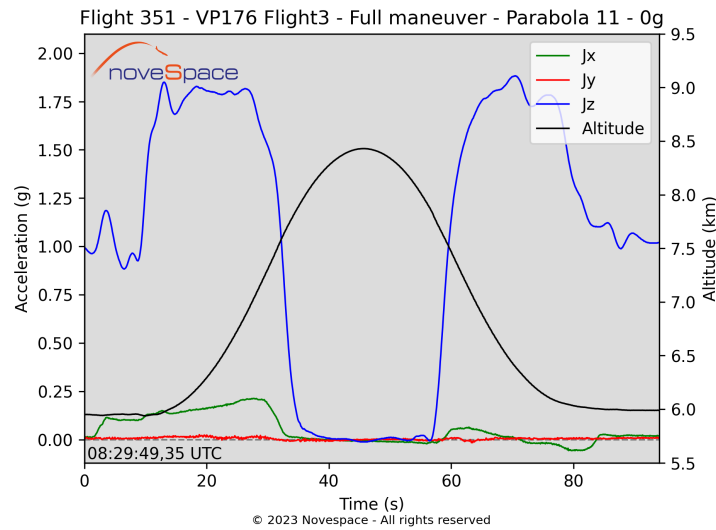


Figure 3.38: Post-Flight acceleration data from Novespace (Day 3, Parabola $n^{\circ} 11$).

Similar to the static analyses previously shown, the point measurements of heat flux for parabolas $n^{\circ} 11$ and 18 recorded during the third day of testing are presented. As shown in Figure 3.40, drops in flux are observed in both graphs in the periods immediately before and after the device movement. In particular, the opening phase, shown in the graph on the left, seems to smooth out these drops. In contrast, the closing phase, shown on the right, seems to exhibit more pronounced flow drops.

Qualitatively, the dynamic closing phase of the device in microgravity ap-

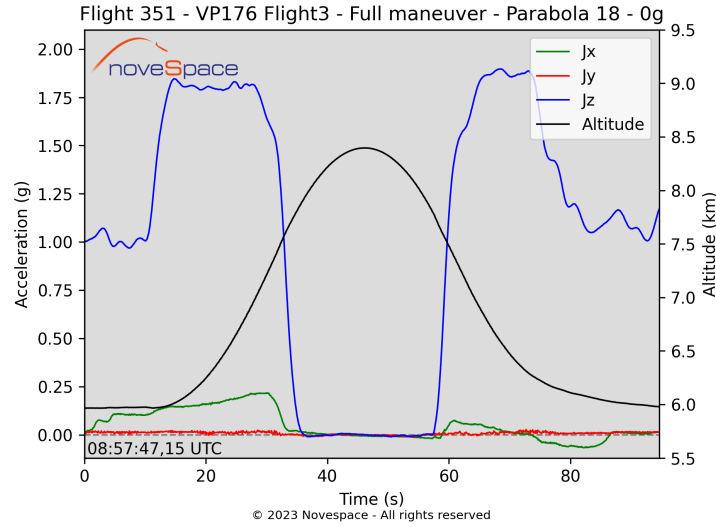


Figure 3.39: Post-Flight acceleration data from Novespace (Day 3, Parabola n° 18).

pears to weakly promote device activation. In contrast, the dynamic opening phase appears to disrupt this process.

To complete this preliminar analysis, Figure 3.41 presents the pressure trends recorded in the evaporator section during parabolas n° 11 and 18 on the third day of testing. These correspond to the dynamic opening and closing phases of the device, respectively. As shown in the figure, two vertical black lines are present, indicating the dynamic interval of the device under microgravity conditions, similar to the plots of the heat flux data.

In the left plot, corresponding to the dynamic opening phase of the device, the movement appears to be associated with a pressure spike. Conversely, during the closing phase, the movement seems to reduce these pressure fluctuations.

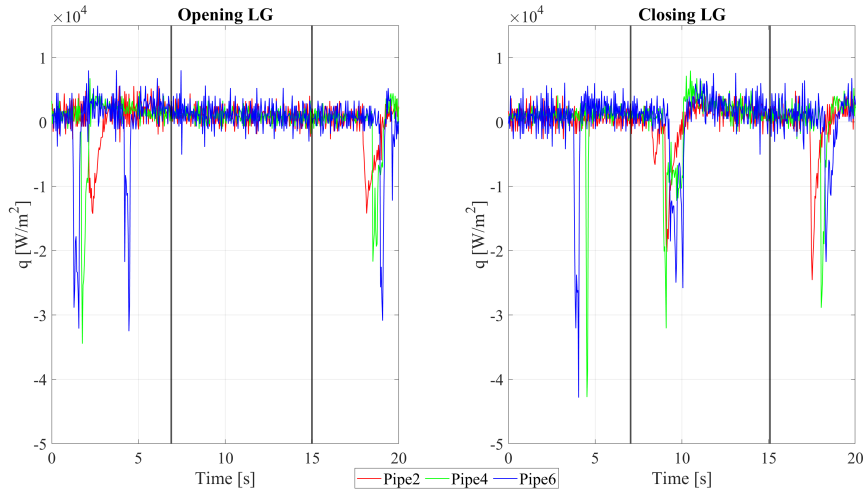


Figure 3.40: Heat flux between the fluid and the wall during dynamic folding and unfolding movement.

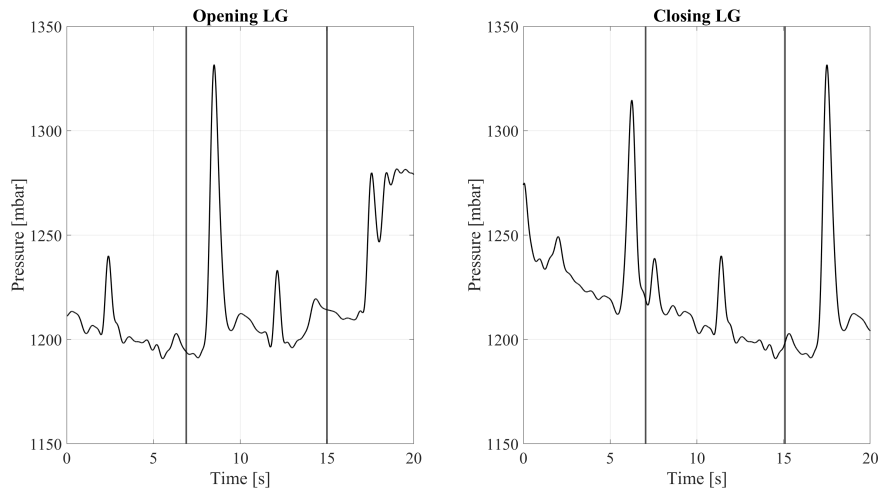


Figure 3.41: Evaporator pressure values during dynamic folding and unfolding movement.

Unlike the static analysis, where there was a correlation between heat flow and pressure values, the dynamic phase analysis does not show a similar relationship. This discrepancy can be attributed to the inherent nature of the test, as device motion introduces transient effects that could be the cause of

the lack of alignment between heat flux and pressure measurements. These dynamic interactions likely contribute to the observed divergence between the two parameters during device operation.

3.3.4 Instantaneous Thermal Resistance

For each analysis, the thermal performance of the heat exchange devices is evaluated and compared using the thermal resistance (Perna et al., 2024), expressed in K/W , as calculated in Equation 3.5. Although this formula is not entirely suitable due to the transient nature of these tests, it provides a useful means of evaluation. Given that steady-state conditions cannot be achieved in this case study, the focus is placed on the instantaneous thermal resistance, which reflects the thermal behavior of the system under varying operational conditions.

$$R(t) = \frac{\overline{T}_{evap}(t) - \overline{T}_{cond}(t)}{Q(t)} \quad (3.5)$$

Where $\overline{T}_{evap}(t)$ and $\overline{T}_{cond}(t)$ are the instantaneous experimentally measured temperatures (± 0.4 °C), at the evaporator and the condenser sections, respectively (Billi et al., 2023).

For completeness of this preliminary data analysis, Table 3.9 presents the instantaneous thermal resistance of the device in the three previously studied static configurations under microgravity, normal-Earth gravity and hypergravity conditions. Given the nature of the test and the inertia of the device, it is important to note that these cannot be considered completely stationary conditions. However, to reduce the impact of transient effects, the instantaneous thermal resistance was evaluated at the final stages of hypergravity, microgravity, and steady flight, as shown in Figure 3.42. These instants of time were chosen as the most suitable to approximate almost stationary conditions in this analysis.

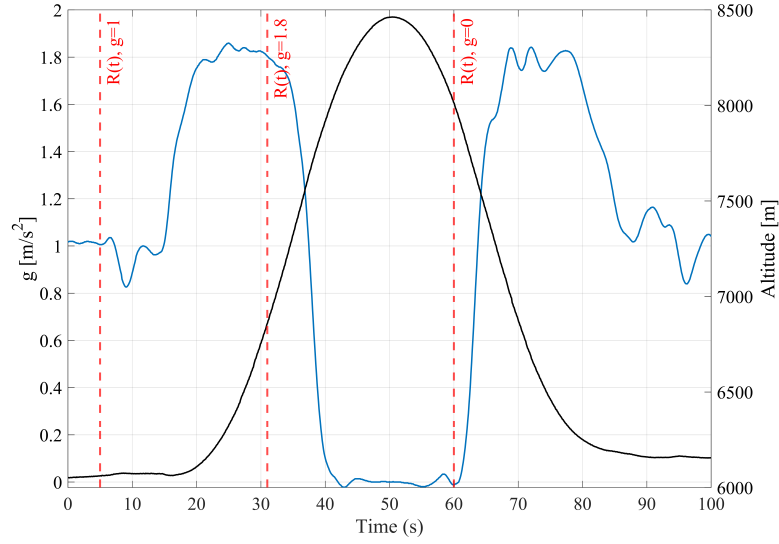


Figure 3.42: Temporal moments at which the Instantaneous Thermal Resistance was evaluated in a generic parabola.

The values of the temperatures used for this calculation, reported in Table 3.9, are those recorded at the end of the hypergravity and microgravity phases, in order to minimize disturbances caused by the system not reaching a steady state.

Analysis of the data collected for different device openings (0° , 90° , and 180°) shows variations in performance (Figure 3.43). The results show that the configuration with the device fully closed (0°) tends to have lower performance than the other angles, regardless of the gravity acceleration values considered.

Based on the Instantaneous Thermal Resistance values, a slight correlation between different gravity levels and the performance of the device can also be observed. Specifically, as the gravitational force increases, the thermal resistance decreases, indicating an improvement in performance. Conversely,

Table 3.9: Instantaneous Thermal Resistance values.

PHP <i>Conf.</i>	g [m/s^2]	$Q(t)$ [W]	$\bar{T}_{cond}(t)$ [K]	$\bar{T}_{evap}(t)$ [K]	$R(t)$ [K/W]
0°	0	56	299	381.8	1.48
0°	1	56	299	378.5	1.42
0°	1.8	56	299	377.5	1.40
~ 90°	0	56	298.5	381	1.47
~ 90°	1	56	298	377	1.41
~ 90°	1.8	56	298.5	376	1.38
180°	0	56	299.3	381.5	1.47
180°	1	56	299.4	377.5	1.39
180°	1.8	56	299.5	377	1.38

as the gravitational force decreases, the thermal resistance increases, reflecting a reduction in performance.

For the 90° and 180° configurations, the values obtained are comparable both in microgravity and hypergravity. However, a difference is observed when the normal-Earth gravity acceleration is considered, where the value for the 90° configuration is intermediate between the fully open (180°) and fully closed (0°) configurations. Data analysis indicates that both device configuration and gravity acceleration influence its efficiency. The observed differences in performance are found to be relatively small. The optimal value is $R(t) = 1.38$ K/W, while the value under the least favorable conditions is $R(t) = 1.48$ K/W. The percentage variation between the optimal and least favorable values is about 7.2%.

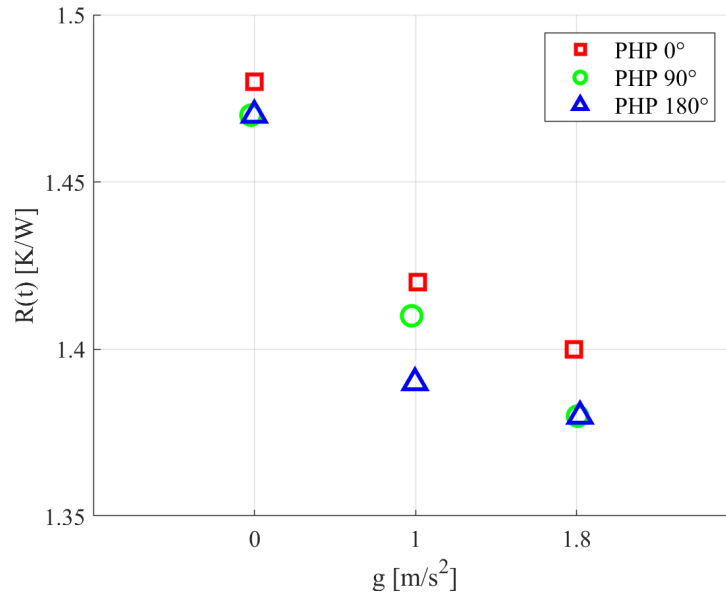


Figure 3.43: Plotting of Instantaneous Thermal Resistances.

3.4 Results

The DEPLOY! Project is focused on studying the performance of a Deployable Pulseating Heat Pipe (*PHP*) prototype under altered gravity conditions. The device was tested once during the ESA Parabolic Flight Campaign (*PFC*) in October 2022, and re-tested with an improved experimental setup during the ESA *PFC* of November 2023. The improvements in the setup include an enhanced actuation subsystem and an upgraded IR Camera, which allows a non-invasive measurements of the device heat transfer behavior in multiple positions during the same flight test. This experiment aims to advance knowledge about the *PHP* device by adding a thermographic analysis during a *PFC*, as it has not been performed previously on this device.

The IR Camera is utilized both for ground tests and during the altered gravity intervals of the flight, enabling comparison between the three different gravity levels. The IR Camera captures images at a frequency of 25 *Hz*. These recordings are then processed and analysed.

The focus of this Chapter is to analyse the behaviour of the *PHP* with different gravity values through a thermographic analysis. The device's thermal boundary conditions are set at 56 *W* and 34 *W* of heating power input at the evaporator section, the first day and the third respectively, and 25 °C as condenser temperature. Observations are made in three different unfolding configurations: *PHP* folded (0°), partially open (90°), and totally unfolded (180°). The tests are conducted during a parabolic flight test and are replicated with the same timings and parameters in a ground test.

Additionally, a preliminary analysis of the device's dynamic behavior in

microgravity was conducted. This analysis revealed a presumed different behavior during folding and unfolding movements. Specifically, the opening movement tends to mitigate temperature drops, while the closing movement appears to amplify them.

Finally, to complete the preliminary analysis, Instantaneous values of equivalent Thermal Resistances were reported based on the data from the first day of flight. These values were compared as a function of both gravitational acceleration and the operational positions of the device.

These results are promising and support the potential utility of the device in different contexts, especially for space applications. However, to fully understand and optimize its performance, further investigation is needed. Future work should focus on in-depth data analysis, but also on repeating the experimental campaign under different conditions and for longer operational periods to validate these preliminary results and refine the device's functionality.

Appendix

Dynamic Test - Heat Maps 1D

The following graphs present the heat maps related to the dynamic tests conducted on the device during the third flight day. Specifically, the first subplot displays the 1D heat map for the entire duration of the recording, which lasts 60 seconds and corresponds to 1500 frames. The second subplot shows the maximum temperature value recorded in each frame. The third subplot illustrates the temperature values from the triggers connected to the accelerometer, enabling the identification of moments of normal gravity, hypergravity, and microgravity. Finally, in this last subplot, vertical black lines indicate the beginning and end of the dynamic phase.

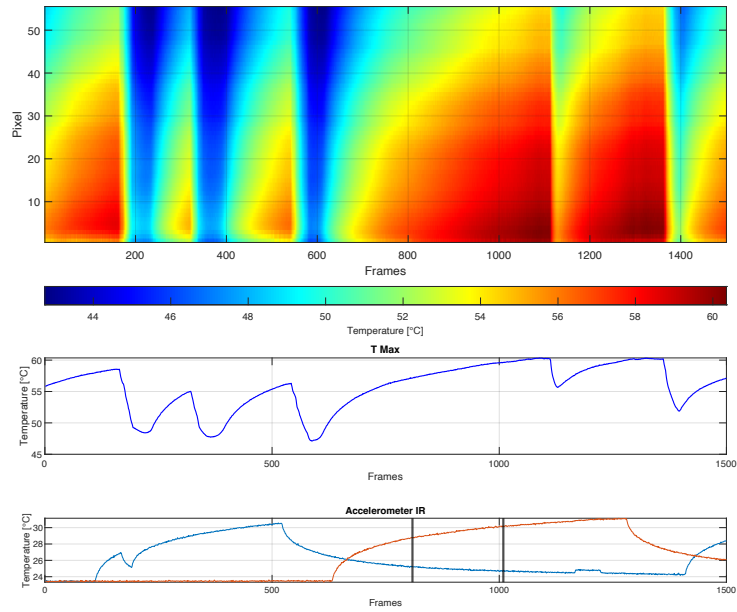


Figure 3.44: Day 3, Parabola $n^{\circ}11$, Pipe $n^{\circ}1$, Dynamic Opening.

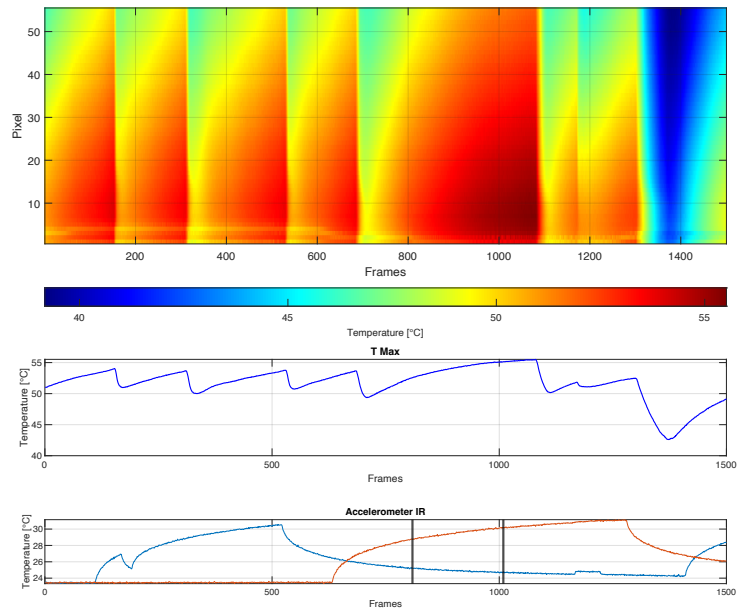


Figure 3.45: Day 3, Parabola $n^{\circ}11$, Pipe $n^{\circ}2$, Dynamic Opening.

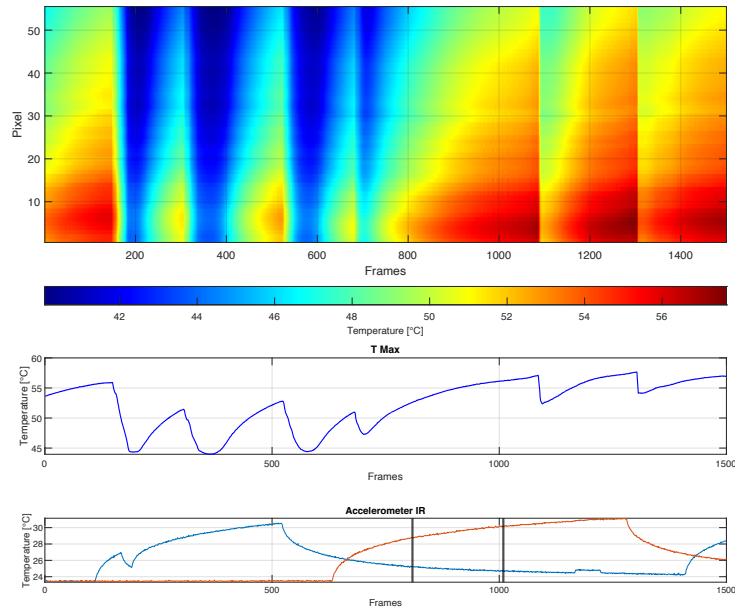


Figure 3.46: Day 3, Parabola $n^{\circ}11$, Pipe $n^{\circ}3$, Dynamic Opening.

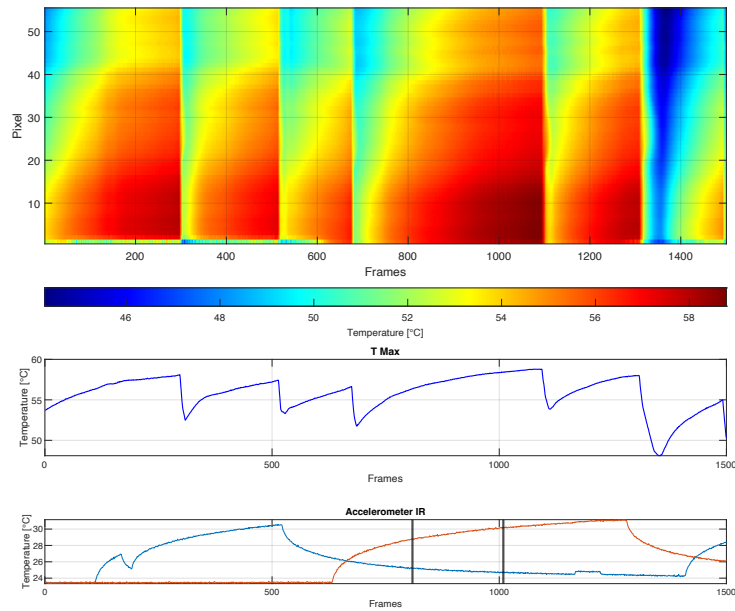


Figure 3.47: Day 3, Parabola $n^{\circ}11$, Pipe $n^{\circ}4$, Dynamic Opening.

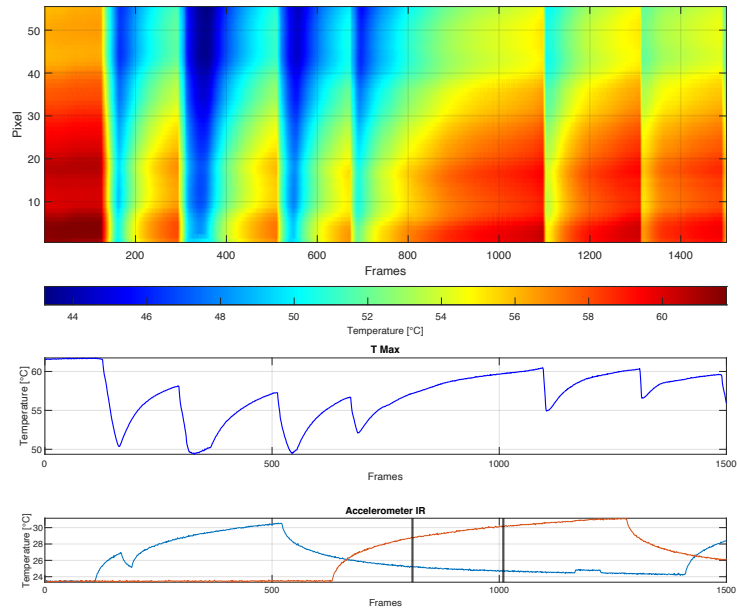


Figure 3.48: Day 3, Parabola n°11, Pipe n°5, Dynamic Opening.

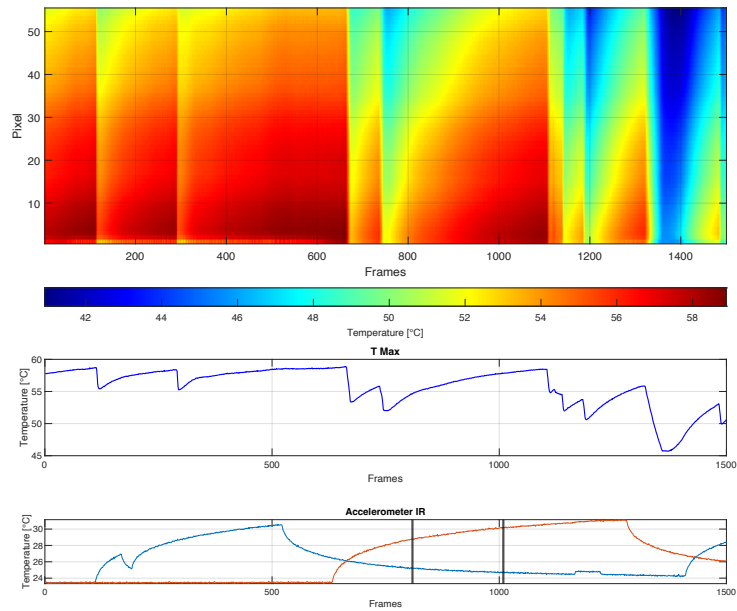


Figure 3.49: Day 3, Parabola n°11, Pipe n°6, Dynamic Opening.

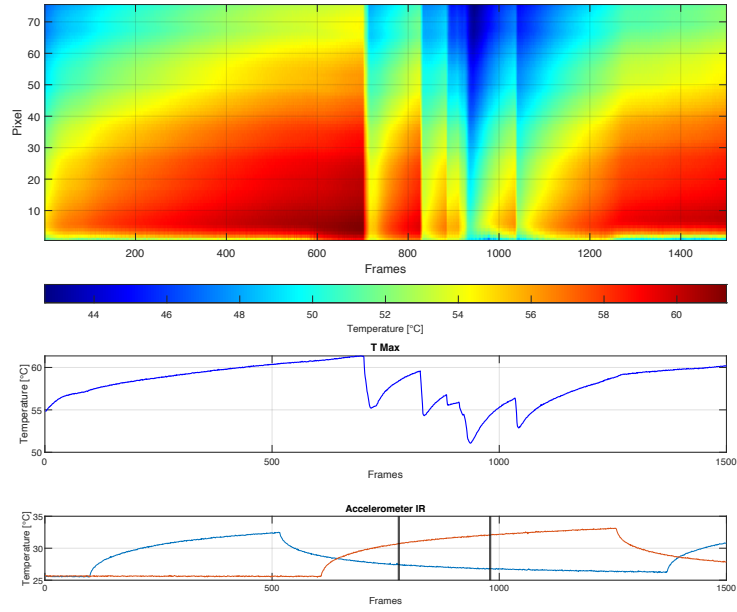


Figure 3.50: Day 3, Parabola n°18, Pipe n°1, Dynamic Closing.

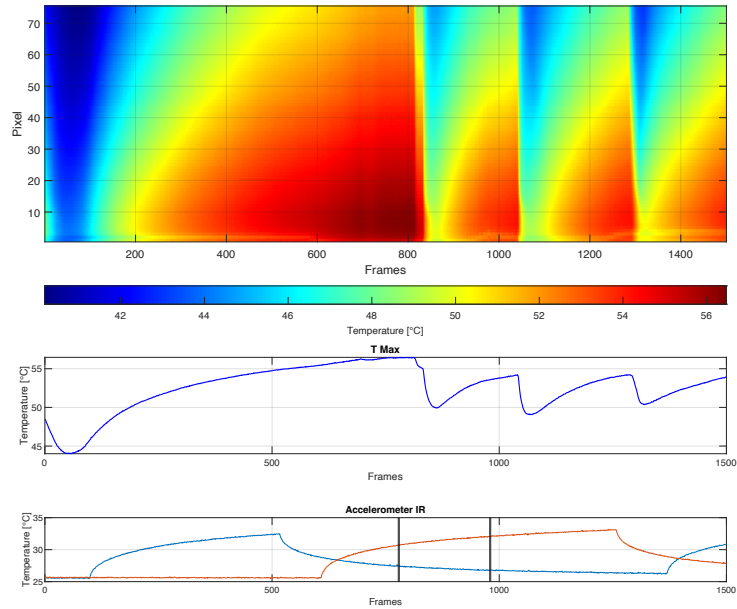


Figure 3.51: Day 3, Parabola n°18, Pipe n°2, Dynamic Closing.

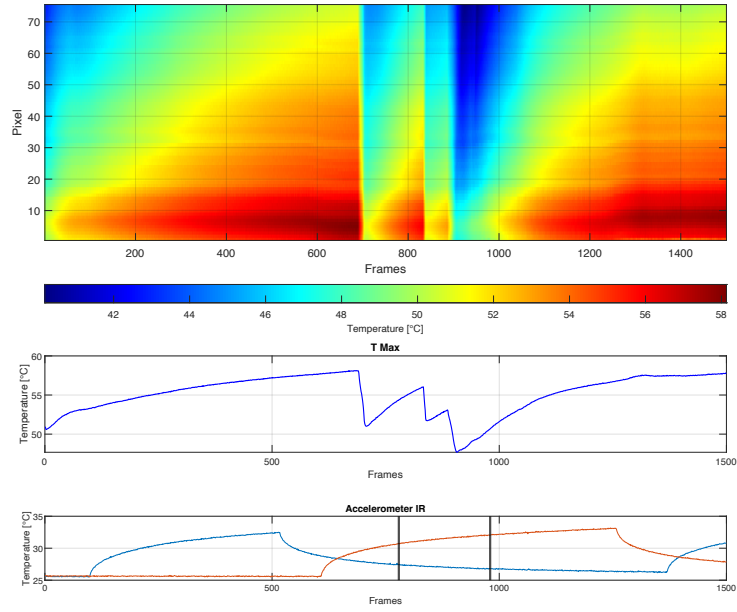


Figure 3.52: Day 3, Parabola $n^{\circ}18$, Pipe $n^{\circ}3$, Dynamic Closing.

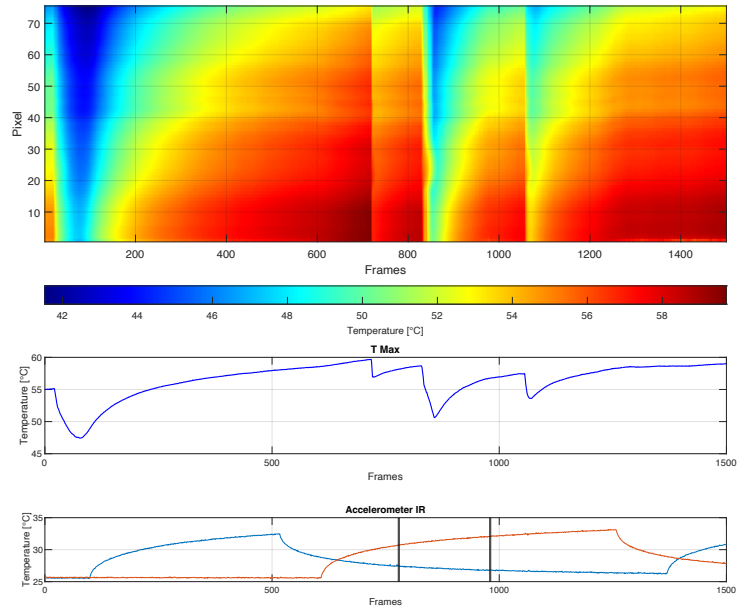


Figure 3.53: Day 3, Parabola $n^{\circ}18$, Pipe $n^{\circ}4$, Dynamic Closing.

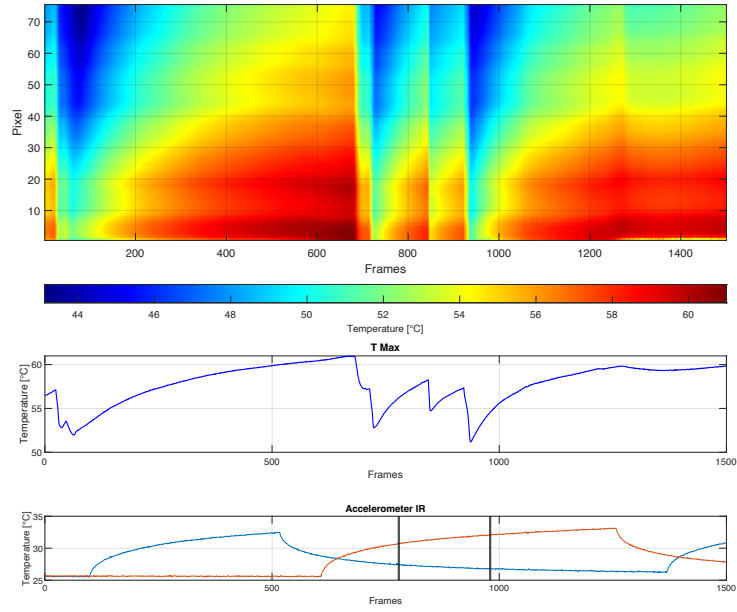


Figure 3.54: Day 3, Parabola $n^{\circ}18$, Pipe $n^{\circ}5$, Dynamic Closing.

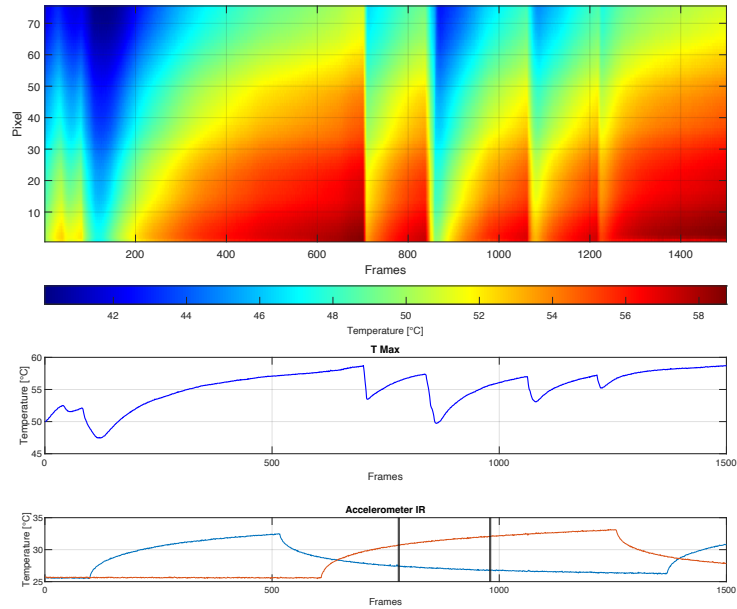


Figure 3.55: Day 3, Parabola $n^{\circ}18$, Pipe $n^{\circ}6$, Dynamic Closing.

IR Camera Flight procedures

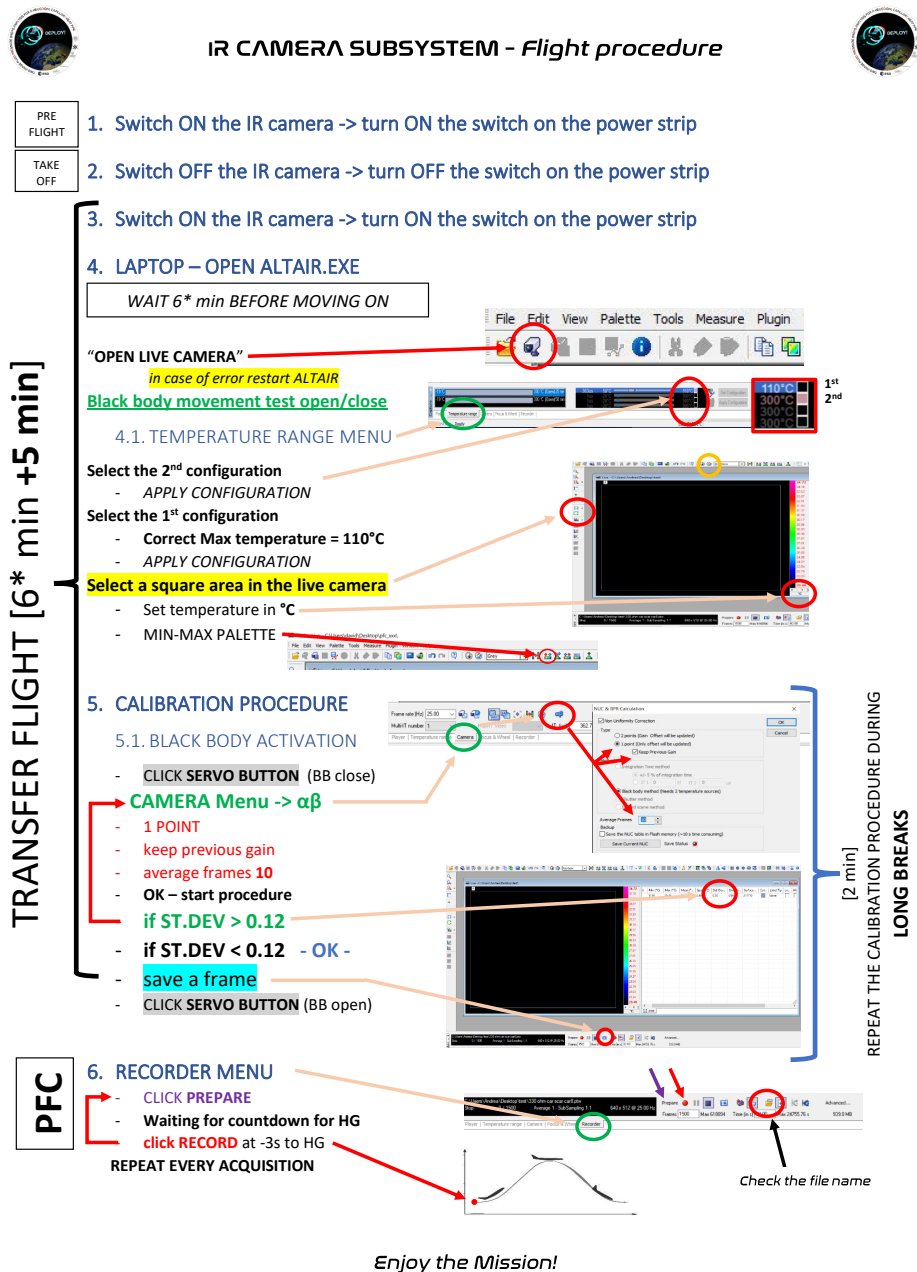


Figure 3.56: IR Camera Flight Procedures.

Chapter 4

Conclusions

This Ph.D. Thesis focuses on the critical importance of Innovation, not only in the field of Industrial Engineering, but in all areas where technological progress and operational efficiency are crucial. Innovation is not only an opportunity, but a necessity to meet current and future challenges. During this three-year research course, I have explored these issues by dividing the Innovation Process into three key phases:

- i. Idea generation.*
- ii. Simulation.*
- iii. Experimental test.*

Each stage was rigorously examined through detailed Case Studies.

4.1 Idea Generation

The first Innovative contribution of this Thesis focuses on the *Idea* evaluation process within an Open Innovation context. In an increasingly interconnected world, companies and organizations need to embrace external contributions to stimulate creativity and enhance the success rate of their innovative initiatives. However, this openness introduces complexity in evaluating ideas from different sources, whether internal or external to the organization.

In response to this challenge, a structured framework for ideas selection and evaluation within the Open Innovation perspective has been developed, integrating both qualitative and quantitative variables into the decision-making process. This framework not only facilitates the selection of the most promising ideas but also encourages collaboration among the various stakeholders involved in the innovation process. The user of this *tool*, will be *potentially everyone in the company*. Adopting this approach leads to an overall improvement in the management of creative resources and accelerates technology transfer, positively impacting the efficiency and effectiveness innovation strategies of the company.

This first case study represents an *Incremental Innovation* that, through its application, can lead to a *Radical Innovation* that will led to a trasformation of the company. In the field of innovation management, the framework stands out as it does not merely perform a static evaluation of ideas but employs a dynamic approach that accounts for market evolution and changing business needs. The results demonstrate that a structured evaluation process not only enhances the quality of strategic decisions but also increases

CHAPTER 4. CONCLUSIONS

the engagement of all stakeholders, both external and internal, in order to promote a more open and collaborative innovation environment.

4.2 Process Improvement

The second Innovative contribution focused on the resolution of the Traveling Salesman Problem (*TSP*), applied to picking processes in a traditional warehouse. Warehouse logistics represents an area where process optimization can lead to significant savings in time and resources, with a direct impact on operating costs and business competitiveness.

In this second Chapter, which is based on the already published work of Montanari et al., 2022 and Bocelli et al., 2024, a warehouse design *tool* has been developed to optimize the picking process, taking into account a wide range of *hardware* and *software* input parameters. The *tool* allows for the modeling of warehouse layouts based on product demand, order volumes, and operational requirements, providing a tailored solution for each specific context. The core of the *tool* relies on solving the *TSP*, adapted to the specifics of warehouse picking, in order to minimize travel times and maximize order fulfillment efficiency. To achieve this, a discrete event simulation method was employed to analyze and optimize picking processes, enabling detailed assessment of system behavior and interactions among various warehouse components.

The results demonstrate that the use of this *tool* can lead to significant improvements in reducing picking times and optimizing resource utilization. Furthermore, the *tool* facilitates informed decision-making during warehouse design or adjustment phases, aiding in the selection of the optimal configuration from both hardware and software perspectives. This integrated approach to warehouse design, supported by discrete event simulation, can also be ex-

CHAPTER 4. CONCLUSIONS

tended to more complex contexts, such as automated or hybrid warehouses, paving the way for further technological advancements.

4.3 Experiments in Microgravity

The third Innovative contribution involved the design and execution of an experiment under altered gravity conditions during Parabolic Flight Campaign. This type of experimentation represents a unique challenge in the field of engineering, as it requires the technologies to be tailored to different operating conditions from those on the ground.

In this third case study, the previously published works of Billi et al., 2024a and Billi et al., 2024b are extended by adding a description of the experiment, as required for the preparation of the ESA Experimental Report (ER), Billi et al., 2023. Preliminary results presented at *ELGRA* 2024 (Saltmarsh, 2024), have also been incorporated. The experimental data and results have been combined to provide a deeper understanding of the behavior of a Pulsating Heat Pipe (*PHP*) heat exchanger, which was analyzed using traditional monitoring techniques, such as thermocouples and pressure sensors, and advanced thermography methods.

The objective of the experiment was to understand how altered gravity affects the operation of the device and its ability to transfer heat efficiently. Parabolic Flight Campaigns provided a unique opportunity to test the *PHP* under both microgravity ($\sim 0g$) and hypergravity ($\sim 1.8g$) conditions, yielding valuable data for the development of space technologies and allowing for an assessment of how normal-Earth gravity ($= 1g$), influences the behavior of the device.

The experimental results highlighted how varying levels of gravity impact both the static and dynamic behavior of the *PHP*, with direct implications

for the design of heat exchangers not only for space missions but also for Earth-based applications.

This study represents an important contribution to research on *PHPs*, offering new insights into the use of these devices in different gravity environments. It also provides a foundation for the development and application of this technology in space missions.

In addition to the analysis of the same *PHP*, this study significantly advances the design of complex, yet reliable and effective experiments. It emphasizes the development of rigorous operating procedures for Parabolic Flight Campaigns, which are essential for conducting experiments on this type of test platform, which are, due to their nature, difficult to replicate.

4.4 Overall Outcome

This Thesis addressed three critical research areas, proposing innovative solutions applicable to *real-world* contexts. The combination of established theories with experimental approaches and practical *tools* has led to concrete results that can be used to improve the efficiency of industrial processes and promote innovation in complex technological domains.

The practical implications of this research are several: from improving *decision-making* processes through the Open Innovation approach, to optimising logistics operations in warehouses and designing advanced technologies for space environments. Each contribution offers insights for future research and development, suggesting potential directions for further exploration of the topics discussed.

Finally, this thesis highlights the importance of an interdisciplinary and integrated approach in industrial engineering, where collaboration between theoretical research and practical experience is essential to meet future challenges. The ability to combine Innovation, Simulation, Experimentation with a *real-world* application will prove increasingly crucial to ensure sustainable and technologically advanced progress in industry and beyond.

In this context, the role of the Engineer will become increasingly central. Engineers will play a *dual role* in bridging the gap between academic research and industrial production, not only by translating scientific discoveries into concrete solutions that can be implemented on a large scale, but also by customising scientific research based on the needs of companies. The ability to combine technical and managerial skills with a strategic vision of inno-

CHAPTER 4. CONCLUSIONS

vation will be crucial to ensure the success of companies in an increasingly competitive and rapidly changing market. The future of engineering will be characterised by a growing responsibility to push technological and industrial progress to new frontiers, fostering the development of a more efficient, sustainable and Innovative Universe.

4.5 Conclusione generale

■ ■ Questa Tesi ha affrontato tre aree di ricerca critiche, proponendo soluzioni innovative applicabili a contesti del mondo reale. La combinazione di teorie consolidate con approcci sperimentali e strumenti pratici ha portato a risultati concreti che possono essere utilizzati per migliorare l'efficienza dei processi industriali e promuovere l'innovazione in sistemi tecnologici complessi.

Le implicazioni pratiche di questa ricerca sono molteplici: dal miglioramento dei processi decisionali applicando i Principi dell'Open Innovation, all'ottimizzazione delle operazioni logistiche nei magazzini e alla progettazione di tecnologie avanzate per applicazioni spaziali. Ogni contributo offre spunti per sviluppare ed implementare future ricerche, suggerendo potenziali direzioni per un'ulteriore esplorazione e approfondimento degli argomenti trattati.

Infine, questa tesi evidenzia l'importanza di un approccio interdisciplinare e integrato nell'Ingegneria Industriale, dove la collaborazione tra ricerca teorica ed esperienza pratica è essenziale per affrontare le sfide future. La capacità di combinare Innovazione, Simulazione e Sperimentazione con un'applicazione nel mondo reale si rivelerà sempre più cruciale per garantire un progresso sostenibile e tecnologicamente avanzato nell'industria e non solo.

In questo contesto, il ruolo dell'ingegnere diventerà sempre più centrale. Gli ingegneri assumeranno un duplice compito nel colmare il divario tra la ricerca accademica e la produzione industriale: da un lato, dedicandosi al trasferimento tecnologico, traducendo scoperte scientifiche in soluzioni concrete e scalabili; dall'altro, customizzando e guidando la ricerca scientifica

per rispondere alle esigenze delle Aziende.

La capacità di integrare competenze tecniche e manageriali con una visione strategica dell'innovazione sarà essenziale per garantire il successo delle imprese in un mercato sempre più competitivo e in rapida evoluzione. Pertanto, il futuro dell'ingegneria sarà caratterizzato da una crescente responsabilità nello spingere il progresso tecnologico e industriale verso nuove frontiere, promuovendo lo sviluppo di un Universo più efficiente, sostenibile e Innovativo.

Se ho visto più Lontano, è perché stavo sulle spalle dei Giganti.
If I have seen Further, it is by standing on the shoulders of Giants.

Sir Isaac Newton

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