

Dedication

Acknowledgement

Abstract

Keywords:

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Glossary of Acronyms

- CAN Controller Area Network
-

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General Introduction

The latest events of the current decade have highlighted the challenges that manufacturers, suppliers, and end customers face during fluctuations in logistics and supply chain processes. Living in a VUCA world—Volatile, Uncertain, Complex, and Ambiguous—requires us to continuously adapt to changes and anticipate future events by preparing our developed environments and scaling our solutions. Simultaneously, it is crucial to maintain high standards that ensure productivity, enhance work safety, and optimize ergonomics.

In this context, the primary objective of intralogistics is to optimize, integrate, automate, and manage internal logistical flows of material and information within distribution centers, warehouses, or manufacturing plants. This subfield focuses on increasing operational efficiency by employing new technologies, such as autonomous robots.

Modernizing industrial environments through intralogistics offers significant potential for companies that adopt and adapt to it. However, convincing potential customers of the efficiency and impact of intralogistics robots presents challenges. These limitations include high training and implementation costs, changes to work routines, and the need for space and process adaptations.

A recent study from CBRE, the world's largest real estate services provider, revealed that European industrial and logistics investments increased by 16% in Q1 of 2024 compared to Q1 of 2023. Despite this, many warehouses are old, repurposed buildings that are unorganized due to the nature of their daily tasks. These brownfield warehouses are expensive to maintain and digitalize but represent ideal grounds for developing and utilizing fully autonomous systems. Unlike AGVs, autonomous vehicles possess the intelligence and capability to plan and execute their plans efficiently. They are designed to adapt to uneven terrains and unorganized working environments given the revolutionary technologies that they hold.

In this context, STILL, a KION group company, has been developing smart intralogistics solutions since its establishment more than a 100 years ago, successfully integrating automation into logistics. STILL offers a wide variety of products that cater to industries ranging from food retail to automotive manufacturing and chemical sectors. Their solutions address various customer challenges, such as reaching high shelves, order picking, palletizing, fleet management, and providing consulting services. Trusted by leading German companies like Siemens, STILL's products and services are renowned for their reliability and efficiency.

The STILL Autonomous Robots department focuses on developing and enhancing smart vehicles. These autonomous robots, with minimal cost-effective input from the warehouse environment, can perceive their surroundings, estimating their positions, efficiently planning future tasks, controlling their movements to reach destinations, executing desired actions, and making corrections if necessary. This focus on smart, autonomous vehicles demonstrates STILL's commitment to pushing the boundaries of intralogistics and automation.

In light of this, this thesis aims to contribute to the process of palletizing by optimizing a local path planning approach applied in the warehouse's stations near the shelves or spots where pallets are located for picking or in free placing areas. The developed approach seeks to plan the near-field path optimally while simultaneously avoiding obstacles.

The objective is to create predictable, repeatable, and explainable vehicle behaviors, demonstrating the autonomous vehicle's ability to generate effective solutions tailored to each specific scenario. By focusing on optimal, pattern-based near-field path planning, this thesis addresses the challenge of navigating complex intralogistics environments, ensuring maximum efficiency and safety in operations. This approach not only enhances the vehicle's performance but also showcases the potential of autonomous technology in transforming modern intralogistics.

This work encloses 4 chapters:

- **Chapter 1** gives a deep insight about the host company's structure, activities and products. Then it dives into the project context and its motivations, the studied problematic, the fundamental aspects of the work, the thesis specifications and, the work methodology.
- **Chapter 2** delves into the state of the art of the work area, then goes through a review of the literature that served as a base of the thesis and gave an overview of the existing solutions. Finally, it presents milestones followed in the course of the thesis work.
- **Chapter 3** explains the development steps of the approach: it presents the mathematical aspect of splines and their implementation in robotic path planning, explains the geometric division of the stations into transition zones, discusses the studied path discrimination approaches, and finally it explores the optimization approaches for the local path planning problem.
- **Chapter 4** explicits the steps it takes to implement the developed approach in the RACK framework, test them in the RACK simulation system, then on the automated vehicle, run different test scenarios and states the obtained results.

Chapter 1

Project scope

Chapter 1

Project scope

Introduction

This chapter is reserved to present STILL GmbH as the host company, its organizational structure, the mother company KION group. It will then proceed to describe the range of products that the company produces. The second part is dedicated to explain the problem statement, the motivation behind this thesis, and the project specifications. The final part will emphasize the work methodology adopted to carry out this project.

1 | Host company: STILL GmbH

1.1 General information about STILL and KION Group and their vision

STILL GmbH, based in Hamburg, Germany, is a leading manufacturer of intralogistics solutions with 14 locations in Germany and a global sales network spanning 246 locations. Operating under the KION Group, Europe's largest forklift truck manufacturer, STILL boasts over 100 years of experience. The company develops highly efficient, client-tailored products, serving businesses of all sizes with a wide range of forklift trucks—from manually driven forklifts to high-reach trucks and fully automated vehicles—alongside consultancy services and software solutions.

STILL prioritizes smart logistics and energy optimization while maintaining award-winning product quality, catering to industries such as food and retail, automotive, and electronics. Employing over 9,000 people across departments like sales and marketing, research and development, production, mechatronics, and quality assurance, STILL remains at the forefront of intralogistics innovation.

KION Group is one of the global leaders in the fields of industrial trucks and supply chain

solutions. It is the mother company of: Linde, Dematic Baoli, OM, Fenwick, and STILL who produce the goods and services of the group as detailed in Figure 1.1.

Present in 4 continents and hiring more than 42000 employees, KION's strategy is to ensure profitable and sustainable growth while focusing on Automation and robotics deployment as one of the main leaders of this growth.

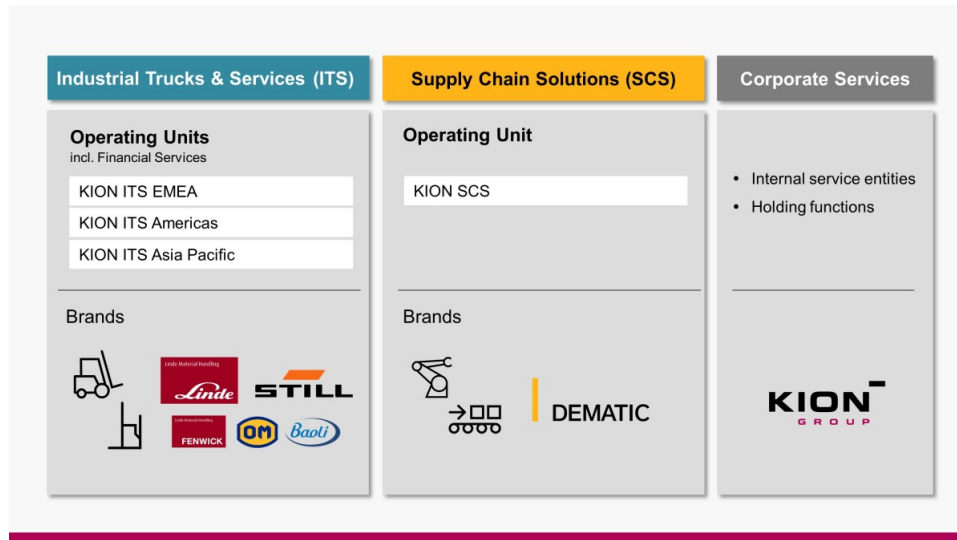


Figure 1.1: KION segment services and companies [1]

1.2 KION Management Hierarchy

The company is composed of departments managing the operations in all companies that are divided by scope of interest like R&D, Management, finances, etc.. Figure 1.2 illustrates the different areas of responsibility of the Executive Board. The Autonomous vehicles team belongs to the Mobile Automation department under CTO.

1.3 STILL Products

The 2017-established Autonomous vehicles team aims to develop fully automated solutions that leverage novel technologies to create innovative services delivered through forklift trucks. The vehicles are developed while keeping safety and high-performance as the main priorities.

iGo neo shown in Figure 1.6 is one of the main products developed by the department, it is a low level order picker transformed into the agent's autonomous assistant. Functioning in autonomous or semi-autonomous modes, it can follow the operator and their pace while avoiding obstacles and perceiving their surroundings as well as pick and place pallets in designed areas. Its added value is in preserving ergonomics of the operators by preventing heavy load carrying for long distances and decreasing the driving ascents and descents by 75% thus increasing the personal and collective performances [3].

CEO Chief Executive Officer	CFO Chief Financial Officer	CPSO/ Labor Relations Dir. Chief People and Sustainability Officer	CTO Chief Technology Officer	President KION SCS & ITS Americas	President KION ITS EMEA	President KION ITS APAC
Corporate Office	Corporate Accounting & Tax	Corporate Human Resources	Product Strategy & New Technologies	OU KION SCS (Americas, EMEA & APAC)	OU KION ITS EMEA	OU KION ITS APAC
Corporate Strategy	Corporate Controlling	Health & Safety	Product Creation Processes, Tools & Data	Global SCS Supply Chain	Sales & Service	KION ITS China
Corporate Communications	Corporate Finance/M&A	Sustainability	Module & Component Development	KION SCS Global Execution & Sustainability	Operations	KION ITS Rest of APAC
Legal	KION GROUP IT	HR KION ITS EMEA	Product Development	KION SCS Global Commercial & Strategy	Multi Brand and Product Mgmt.	Operations
Corporate Compliance	Investor Relations	HR KION ITS APAC	Procurement	KION SCS Global Products & Solutions	Business Development	Strategy, M&A
Business Transformation	Finance KION ITS EMEA	HR KION SCS	Quality	KION SCS Marketing & Communications	Human Resources*	Human Resources*
Internal Audit	Finance KION ITS APAC		New Energy	KION Digital Solutions	Finance*	Finance*
	Finance KION SCS		Mobile Automation	OU KION ITS Americas		
				KION ITS North America		
				KION ITS South America		
				Human Resources*		
				Finance*		

Figure 1.2: KION Executive Board responsibilities as of 01.2024 [2]

As STILL specializes in forklift trucks, it counts many other products. Trucks are either Diesel or Gas fueled, or electric trucks that use Li-Ion batteries. Depending on the client's warehouse type, they can choose from a vast range of reach trucks Figure 1.3, hand pallet trucks Figure 1.4, double stacker trucks Figure 1.5, and Automated industrial Trucks Figure 1.6 [4].



Figure 1.3: STILL reach truck



Figure 1.4: STILL hand truck



Figure 1.5: STILL reach truck



Figure 1.6: STILL hand truck

Despite the impressive capabilities of the iGo neo and similar autonomous vehicles, the implementation of such advanced technology brings up several challenges, particularly in ensuring reliable and predictable behavior under all operating conditions. This leads to a key motivation for further investigation and improvement in the field.

1.4 Motivation and Problem Statement

While autonomous vehicles can be highly reliable and efficient in carrying out various tasks, their behavior is not always predictable or easily explained. The output often exhibits a stochastic nature. For example, an obstacle-avoiding solution planned by the autonomous vehicle may be safe and correct but might follow an unusually shaped path.

Such stochastic behaviors can lead to a lack of trust and interest in robotized forklift trucks from a customer's perspective. This unpredictability can cause customers to question the system's repeatability, fearing that it may not perform consistently in critical situations. Moreover, the unexpected nature of these behaviors can make it difficult for operators to understand and anticipate the vehicle's actions, further reducing confidence.

Adding to these concerns, many autonomous systems, particularly in the intralogistics sector, require significant commissioning efforts before they can be implemented in a new environment and begin their service. Whether it's a required software, sensors, or measurements, these systems demand substantial time and financial investment—two crucial resources that we aim to optimize.

As engineers, we are committed to developing optimal solutions that are easy to commission in a new environment. These so-called "plug-and-play" solutions reduce the effort required and allow customers to start benefiting from the autonomous features with just the physical truck on-site and some basic input from the warehouse map, the rest, is online recognition and

processing. This approach significantly enhances the impact and convenience of the technology.

To address these issues, the autonomous vehicles department is dedicated to creating solutions that are not only reliable and efficient but also transparent and understandable. By focusing on explainable autonomous systems, the department aims to build greater trust with customers, ensuring they feel confident in the technology and are more likely to adopt and utilize these advanced robotic solutions.

This thesis discusses one such possible application of autonomous vehicles. The use case involves solving the following problem: as illustrated on Figure 1.7, after the vehicle enters the station- a limited area inside the warehouse where the shelf stands to palletize/depalletize, in predefined positions, it faces the following problematics:

- The vehicle's forks are not facing the destination shelf but rather the opposite direction, so a driving direction change is needed.
- The vehicle is heavy (1200 to 1500 KG) with an overall length of 2500 to 4000 mm which makes it both challenging and dangerous to change directions on its spot [5].
- The pallet docking process has to be very precise to avoid shifts and mistakes.

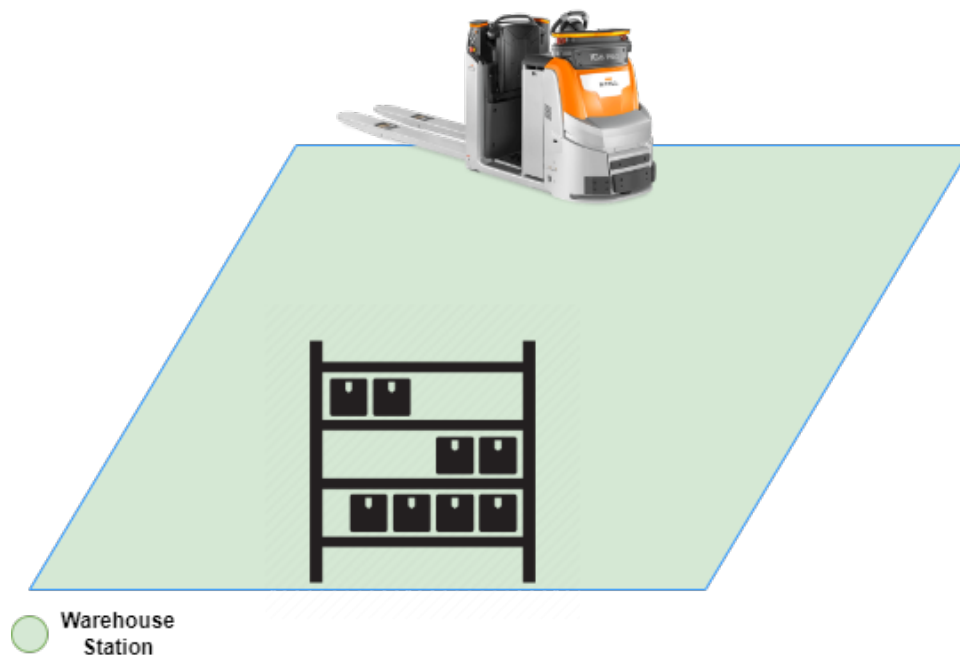


Figure 1.7: Vehicle setting in the station

The first inspiration for the proposed solution was the forklift drivers themselves. The experienced drivers all agree to solve the problematic – if it was to be solved manually, in the

same way: to drive in an arc shape to a point, then to change the driving direction and orienting the vehicle to the destination position.

We would like to solve this problematic in a manner that:

- Imitate the manual driving process to pick a pallet when in the same situation (facing backward of the pallet).
- Implement a predictable local path planning algorithm for the vehicle operations inside a station.
- Reduce the computational expense used with the global dynamic path planning algorithms implemented through a pattern
- Choose an optimal path out of the various paths that can be driven.

1.5 Work Structure and Methodology:

Our team adopts an Agile Scrum methodology showcased in Figure 1.8 to ensure efficient and flexible project management. Here's how we approach our work:

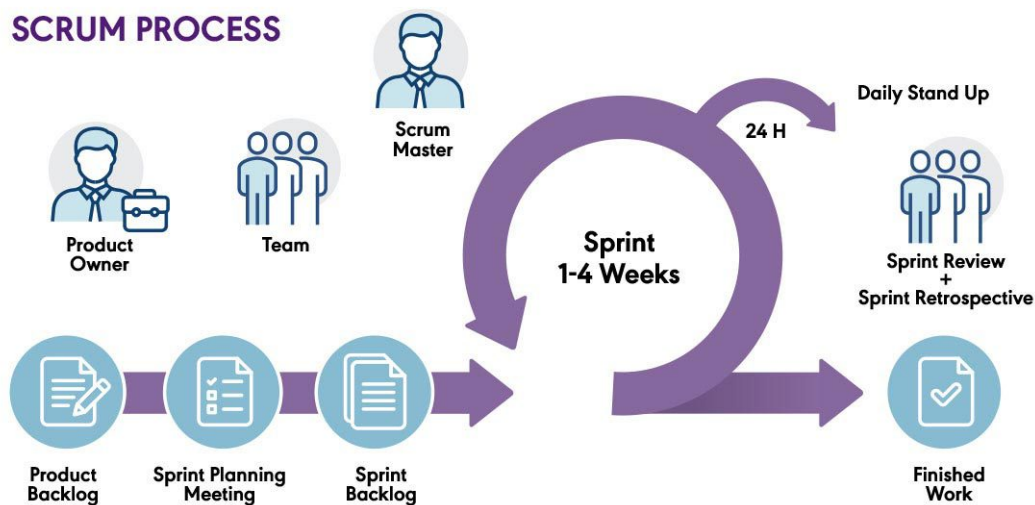


Figure 1.8: Agile Scrum Process [6]

1.5.1 Agile Scrum Framework:

- **Jira:** We use Jira to organize and track our tasks and progress. Jira allows us to create and manage tickets, which are detailed records of tasks, bugs, or features that need attention. Each ticket is assigned to team members and tracked through its development stages until completion.

- **Sprints:** Our work is organized into 2-week sprints. Each sprint is a focused period where we aim to complete a set of predefined tasks. At the start of each sprint, we hold a meeting to review the previous sprint: every team member presents their completed tickets, and communicates the changes or blockers that appeared during the process and plan for the next sprint: decide which tasks will be tackled during the sprint. This helps us maintain a steady pace and regularly deliver increments of our project.
- **PI Planning:** Every quarter, we engage in Program Increment (PI) planning with the mobile automation teams. The PI happens in two phases: each team prepares their planning for the next 3 months, then it is discussed and tailored again in a bigger round. This planning session helps us align our goals and strategies for the upcoming quarter. We review progress, set objectives, and coordinate with other teams to ensure that our work is aligned with broader project goals and company vision.
- **Daily Standups:** We hold 15 minutes long daily standup meetings to keep everyone on the same page. During these meetings, team members share updates on their progress, discuss any challenges they are facing, and outline their plans for the day. This practice promotes transparency and quick problem-solving.

1.5.2 Version Control:

- **GitHub:** We use GitHub for version control and code management. GitHub allows us to collaborate on code, track changes, and manage different versions of our project. Each team member can contribute to the codebase, and we use pull requests to review and integrate new features.

1.5.3 Communication and Collaboration:

- **Microsoft Teams:** We use Microsoft Teams for real-time communication and collaboration. Teams provides a platform for chatting, video calls, and sharing files, facilitating smooth and efficient interactions among team members.
- **Microsoft Outlook:** Outlook is used for email communication and scheduling. It helps us manage meetings, track important messages, and coordinate tasks and deadlines.

By integrating these tools and practices, we ensure a structured yet flexible workflow, enabling us to adapt to changes, communicate effectively, and deliver high-quality results.

Chapter 2

State of the Art

Chapter 2

State of the Art

Introduction

The intralogistics sector is currently being revolutionized by the integration of digital tools like connected industries and robotics. The cluttered and highly dynamic nature of this environment makes it challenging to successfully implement robotic solutions.

The first steps in digitalizing logistic processes with robots involved the use of Automated Guided Vehicles (AGVs). First introduced in 1955, AGVs perform tasks like material handling. Their main advantage is that they are driverless and can be controlled by top-level software, where task planning is managed [1]. The vehicles then receive intermediate points they should pass through on their way from the start to the endpoint. However, the decentralized decision-making approach of AGVs makes them unresponsive to changes in their environment. For example, AGVs localize themselves using specific and precise anchors physically located in their workspace (TODO: add pictures of the anchors: reflectors..). This localization mechanism helps them follow the assigned path. As a result, even a simple environmental change requires an update of the measurements and maps on which the planning is based. Another example is that an AGV is unable to plan and execute a solution if it encounters an obstacle on its way to the goal. In such cases, the AGV's reaction is to stop and wait for top-level instructions [2]. This behavior decreases productivity and disrupts the planned sequence of tasks.

To overcome these disadvantages of AGVs, Autonomous Mobile Robots (AMRs) were introduced. AMRs are equipped with a decentralized control system, enhanced perception of their surroundings through more complex hardware, and advanced software to manage and integrate these hardware additions.

In addition, they grant a fast integration into new environments due to smart perception and recognition technologies. AMRs use this data as input to smart algorithms that enable it to plan its missions, navigate to its destination, avoid collisions, and execute missions all while collaborating with humans in the working space. The Autonomous vehicles do not require an automation expert or a roboticist's presence to be configured or to deal with complex situations. It is able to solve such situations individually due to the scalable software that it has on board.

On the one hand, this evolution enables AMRs to navigate more dynamically and adaptively within intralogistics environments, improving overall efficiency and responsiveness. On the other hand, the level of flexibility that AMRs brings important safety and efficiency considerations.

One of the main challenges is developing the navigation mechanisms. In a logistics environment, it is crucial to comply with the nature of the workspace. The AMR should recognize the location of materials to be handled and be able to navigate to and from those locations to next missions. Building a flexible and efficient solution requires a deep understanding of the situations and special cases that the vehicle may encounter and a study about how to create scalable solutions for such events.

Before diving into the methodologies and technologies used to address this thesis' topic, it is relevant to examine the related works. This research will serve later in the thesis as a guiding outline. Literature helps to display the level of progress that other researchers reached in similar topics, prevents re-invention of existing concepts, and pushes to ethically exploit the developed technologies. For this thesis, it is important to deeply examine the research papers and scientific resources to build a solid foundation of knowledge, identify the gaps in some studies, and propose novel solutions.

In this context, this thesis, and specifically this state-of-the-art report, delves into near-field path planning (path planning + local (benchmarks)) for mobile robots in general and for intralogistics AMRs specifically. Then, it examines possible solutions for path creation and generation (pattern paths + splines). Afterwards, it studies the decision-making science approaches that can be used to evaluate and optimize path suggestions (metrics + optimization techniques). Finally, this chapter outlines the methodology to be followed throughout this scientific work(fig2).

Chapter 3

Design and development of the Control Interface

Chapter 3

Design and development of the Control Interface

Introduction

In this chapter, we delve into the heart of the iHEX system’s functionality – the Control Interface (CI) software which forms the cornerstone of communication and control, enabling seamless interaction between the MC and the SCs. This chapter presents the design, development, and test of the CI on both the MC and SC and the integration of both of them.

1 | Control Interface (CI) on the MC

1.1 Multithreaded architecture:

In the design of the CI on the MC, a multithreaded architecture was adopted to meet the dynamic and concurrent demands of communication, command processing, monitoring, and logging within the iHEX system. The use of multithreading was essential in ensuring a responsive and efficient operation of the control software.

1.1.1 Multithreading need

A fundamental requirement for the Control Interface is its ability to handle multiple tasks simultaneously. The MC must efficiently **manage communication with the server, manage communication with the SCs via CAN Bus, continuously monitor the health of the CAN network, and maintain a log of system activities**. This multifaceted demand necessitates a multithreaded approach to prevent bottlenecks and ensure timely execution.

1.1.2 The `<pthread.h>` library

Chapter 4

Design and development of Printed Circuit Boards

Chapter 4

Design and development of Printed Circuit Boards

Introduction

In Chapter 4, we dive into the essential process of creating the electronic foundation of the iHEX system—Printed Circuit Boards (PCBs). These PCBs serve as the crucial framework where all the electronic parts of the iHEX system come together, ensuring seamless communication and control. This chapter explores the design, development, and roles of four specific PCB types: Main PCB, IO PCB, LED PCB, and Dock PCB.

1 | Architecture

Based on the specifications and the company needs, we designed the global hardware architecture. It is mainly composed of 4 designed PCBs:

- Main PCB is the motherboard that brings the main electronic components of the SC together. Each SC is composed of one Main PCB that is connected directly to an IO PCB.
- IO (Input-Output) PCB mainly ensures connectivity and interaction with the other SCs. It is connected to the Main PCB on one side. On the other side, it is connected whether to IO PCBs of other static SCs or Dock PCBs.
- Dock PCB ensures the interaction and control of the iHEX mobile element newly connected. If it exists, whether in a static or mobile element, it is connected to the SC through the IO PCB.
- LED PCB controls the LED strip. Each LED PCB is part of a SC. It is plugged-in directly on the Main PCB.

General conclusion

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Annexes