Learner Centric Advanced Manufacturing Platform

Digital Technologies 4.0 and Green Transition Impacts on Supply Chain Management

WP3 – Observatory - D3.2 - M36 - Digital Technologies 4.0 and Green Transition Impacts on Supply Chain Management

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GLOSSARY AND/OR ACRONYMS

AFDET - French Association for the Development of Technical Education
AFM - Asociación de Fabricantes de Máquina Herramienta- Machine Tool Manufacturers Association
AFNOR - French association for standardisation
AI - Artificial Intelligence
AR - Augmented Reality
CAGR - Compound Annual Growth Rate
CAM - Computer-Aided Manufacturing
CMMS - Computerized Maintenance Management System
CNC - Computer Numerical Control
CoVE - Centres of Vocational Excellence
EaaS - Equipment-as-a-Service.
EQF - European Qualification Framework
ESCO - European Skills, Competences, Qualifications and Occupations
FCS - Finite Capacity Scheduling
GSCM - Green Supply Chain Management
HVET - Higher Vocational Education and Training
ICS - Infinite Capacity Scheduling
IoT - Internet of Things
IT - Information Technology
IUT - University Institute of Technology
LCAMP - Learner-Centric Advanced Manufacturing Platform
LLM - Large Language Model
MPS - Master Production Schedule
MRP - Material Resource Planning
MV - Mecanic Vallée
NLP - Natural Language Processing
PdM - Predictive Maintenance
PLC - Programmable Logic Controller
SME - Small and Medium-sized Enterprises
S&OP - Sales and Operations Planning
S&OE - Sales and Operational & Execution
TKNIKA - Centre for Applied Research in Vocational Training in the Basque Country.
TPM - Total Productive Maintenance
VR - Virtual Reality
WP - Work Package

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EXECUTIVE SUMMARY

The LCAMP (Learner-Centric Advanced Manufacturing Platform) project, under the CoVE initiative, aims to strengthen regional skill ecosystems in Advanced Manufacturing through collaboration, resilience, and innovation.

This report explores the combined impacts of Industry 4.0 digital technologies and the green transition on Supply Chain Management (SCM) and related workforce development across Europe. Developed by the LCAMP Observatory and led by the French cluster Mecanic Vallée and the Campus des Métiers et des Qualifications Industrie du Futur, with the support of partners located in Germany, Italy, Slovenia, and the participation of Turkey, the report aims to provide strategic insights for SMEs, training centres, and policymakers to help align industrial transformation with education and skills development.

As industries confront growing pressure from geopolitical disruptions, climate goals, and market volatility, supply chains are undergoing a profound transformation. Digital solutions - such as Artificial Intelligence (AI), the Internet of Things (IoT), cloud and edge computing, blockchain, and advanced analytics - are enabling more responsive, data-driven, and sustainable SCM models. In parallel, environmental regulations and carbon reduction targets are accelerating the shift toward circular and low-emission value chains.

The main objectives of this report are to:

- Assess how digital and green transitions reshape SCM processes (Profit Planning, S&OP, MPS, MRP, FCS/ICS), so called SCM 4.0 in this report.
- Identify barriers and opportunities for SMEs adopting SCM 4.0.
- Evaluate the evolving skills and training needs linked to these transitions.
- Provide actionable recommendations for vocational education and training (VET) systems.

Methodology

The analysis combines a comprehensive literature review, expert interviews, and targeted surveys conducted with 176 SMEs and 70 VET centres across five countries (France, Germany, Slovenia, Turkey, and Italy). The study follows a structured methodology developed by the LCAMP Observatory to assess relevance, employability, technological impact, and training implications.

Key Findings

- **Technological adoption is accelerating**: AI, IoT, and cloud-based tools enhance forecasting, inventory optimization, and collaboration, improving operational agility and cost-efficiency.
- **SMEs face specific challenges**: Despite the benefits, SMEs encounter barriers such as high implementation costs, limited expertise, and fragmented digital maturity.
- **Workforce skills are misaligned**: New SCM paradigms require hybrid skill sets - data literacy, systems thinking, and sustainability awareness - that are often absent in current training offers.
- **VET systems lag behind**: Training centres must urgently revise curricula to include digital SCM concepts, AI-driven planning tools, and environmentally responsible logistics.
- **Sustainability is a growing priority**: Companies must address complex issues like Scope 3 emissions, circularity, and regulatory compliance, reinforcing the strategic role of SCM in achieving climate targets.

Recommendations

To harness the full potential of SCM 4.0 and ensure equitable access for SMEs, the report recommends:

- Strengthening **collaboration between industry and VET providers** to co-develop agile, up-to-date training content.
- Increasing **public-private investments in digital and green upskilling** initiatives.
- Promoting **hybrid learning formats** and modular approaches to address SMEs' time and resource constraints.
- Enhancing **support for SMEs** through targeted funding, awareness programs, and capacity-building tools.
- Embedding **sustainability goals** more explicitly in supply chain strategies and educational content.

This report provides a strong overview to guide European stakeholders in shaping the future of supply chain practices and education. It underlines the urgent need for coordinated action to foster innovation, resilience, and sustainability across the supply chain ecosystem.

1. INTRODUCTION

1.1. PURPOSE OF THE REPORT

As industrial ecosystems face mounting complexity and volatility, managing supply chains with precision, flexibility, and sustainability has become a strategic imperative. Traditional supply chain models—often siloed, manually driven, and reactive—struggle to meet the demands of an interconnected, fast-changing global economy. In response, Supply Chain Management (SCM) is undergoing a profound transformation, accelerated by the twin forces of digital innovation and the green transition.

The emergence of Industry 4.0 technologies—including Artificial Intelligence (AI), the Internet of Things (IoT), Blockchain, Cloud Computing, and Big Data—has paved the way for **SCM 4.0**: an intelligent, integrated, and data-driven approach to supply chain operations. At the same time, new sustainability imperatives are pushing companies to rethink logistics, sourcing, production, and distribution from a circular and low-carbon perspective. In this context, SCM 4.0 is not just a digital upgrade—it is a strategic enabler for resilience, agility, and environmental responsibility.

For Small and Medium-sized Enterprises (SMEs), the adoption of SCM 4.0 offers critical advantages: enhanced forecasting, improved inventory and resource planning, cost savings, and improved responsiveness to disruptions. However, significant obstacles remain, including limited investment capacity, fragmented digital maturity, and skill shortages.

Vocational Education and Training (VET) institutions play a central role in addressing these challenges by preparing the workforce for new supply chain paradigms. As supply chain roles increasingly demand digital fluency, data analysis capabilities, and cross-functional coordination, training programs must evolve to reflect these new requirements.

This report explores how SCM 4.0 is transforming supply chain practices across Europe, analyses its impacts on SMEs and workforce development, and provides strategic recommendations for SMEs, VET providers, and policymakers. Through real-world data, expert insights, and cross-country perspectives, it offers a roadmap for embracing the future of sustainable and digitally enabled supply chains.

This report explores how **emerging digital technologies (Industry 4.0)** and **green transition trends, with a focus on recent Artificial Intelligence developments,** are reshaping **Supply Chain Management (SCM 4.0)** concepts, tools, activities, and workforce demands. It specifically examines the impact on traditional and modern SCM processes, including **Profit Plan (PP)**, **Sales and Operations Planning (S&OP)**, **Master Production Scheduling (MPS)**, **Material Requirements Planning (MRP II)**, and the role of **Finite and Infinite Capacity Scheduling** within the evolving industrial landscape? Additionally, the study also explores how these changes affect the **workforce** and **vocational education and training (VET) pathways**.

This report aims to provide actionable benchmarks and strategic insights for two key audiences:

- For SMEs: It offers **an overview** of new **SCM concepts and tools, that we call SCM 4.0 in the report**, addressing challenges, and leveraging emerging digital technologies to enhance Supply Chain Management efficiency.
- For VET Institutions: It outlines how training programs could align with industry needs, ensuring that workers are equipped with new **Supply Chain Management concepts and tools**-related competencies that support Industry 4.0 and green transition goals.

1.2. METHODOLOGY

The LCAMP Observatory methodology is described in the Observatory, process cycle chapter included in (D3-1-Observatory-Methodolgy-Final-Version-1-1.Pdf, n.d.) document.

It includes:

- The methodology to select jobs to analyse
- The methodology to analyse the impacts
- The methodology to validate the Sub-Report

This year, an additional criterion has been added to justify the selection of the field of observation:

- Relevance of the “Field to Observe” based on the 6 criteria previously described in the methodology (existing jobs, trends impacts, employability, strategic topic, education level, training courses Impact).
- Added value for industrial processes: the subject is included in at least one of the 7 transformations analysed in WP7 initiative which is about ADvanced MAnufacturing scans: LCAMP initiative supporting the transformation of SMEs (‘SME - VET Connection’, n.d.).

In order to clarify the objectives of each stage and to control the planning and the main deadlines of the process, the methodology has been clarified compared to previous years. As shown in this diagram, stages 3 and 4 have been divided into 4 distinct phases:

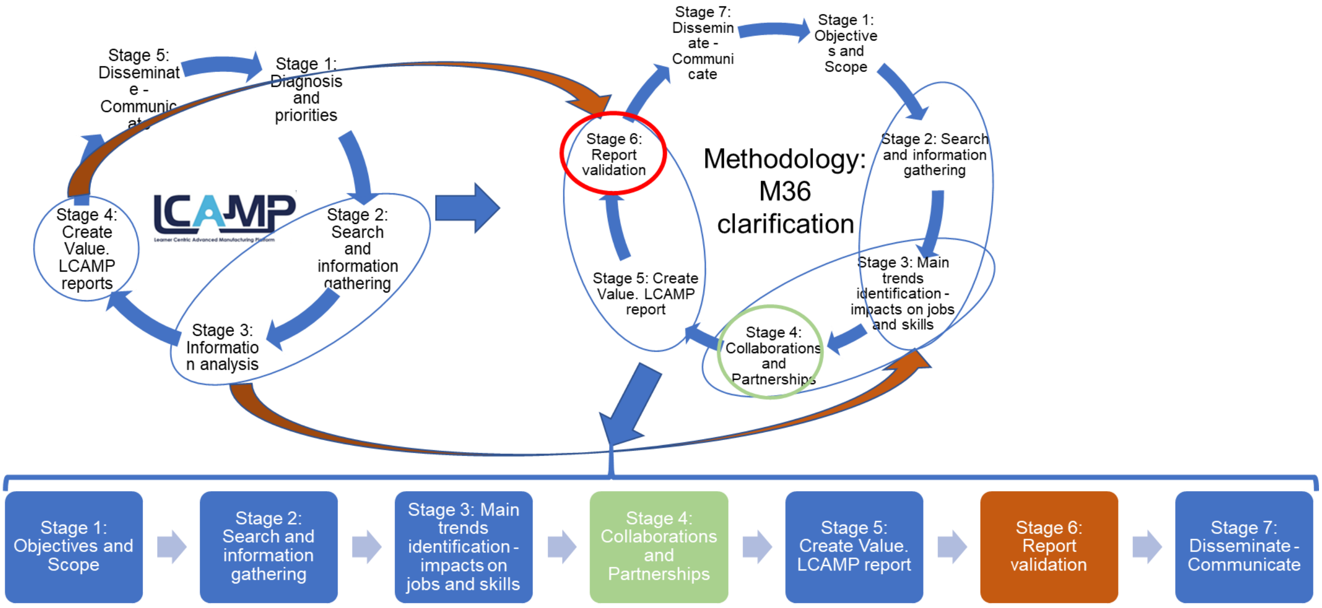

Figure 1. LCAMP Observatory methodology

Stage 4: The insights presented in this report are based on a **comprehensive analysis**, combining:

- **Literature review** of new **SCM concepts and tools** trends, technologies, and market data
- **Survey data** from SMEs and VET institutions across multiple European regions.

This structured approach ensures that the report provides **both strategic insights and practical guidance**, making it a **valuable resource for decision-makers in SMEs and the VET sector**.

In addition to the literature review and discussions with experts in the field, it was decided to carry out surveys of SMEs and VET centres to reinforce the conclusions drawn from the literature review.

1.2.1. STAGE 1 - JUSTIFICATION OF OBJECTIVES AND SCOPE

This study, conducted as part of the LCAMP Observatory, **by LCAMP partners from France, Germany, Turkey, Italy, Slovenia and Turkey** explore the intersection of emerging digital technologies 4.0, green transition trends, and Supply Chain Management (SCM), with a specific focus on their impacts on industry, workforce, and training programs. The key questions addressed include:

- How do digital technologies and green trends affect SCM concepts, tools, and operations?
- What are the impacts on job roles and workforce competencies?
- How should VET curricula adapt to support these transitions?

A first joint analysis carried out with the French, German, Turkish, Italian and Slovenian partners identified the main reasons for selecting this theme; the present report provides precise information and confirms these initial statements.

Relevance:

- Existing jobs: **SCM** operators are operating within Industrial companies.

Table 1. Example of ESCO Occupation list involved in SCM activities (Professions, n.d.).

Esco code	Esco Occupation Code	Esco Occupation Description
1213.2.2	strategic planning manager	Strategic planning managers create, together with a team of managers, the strategic plans of the company as a whole, and provide coordination in the implementation per department. They help to interpret the overall plan and create a detailed plan for each one of the departments and branches. They ensure consistency in the implementation.
1324.8	supply chain manager	Supply chain managers plan, manage and coordinate all activities related to the sourcing and procurement of supplies needed to run manufacturing operations from the acquisition of raw materials to the distribution of finished products. The supplies can be raw materials or finished products, and it can be for internal or external use. Moreover, they plan and commission all the activities needed to be performed in manufacturing plants and adjust operations to changing levels of demand for a company's products.
1324.8.1	forecast manager	Forecast managers have a deep understanding of the operations of the company, the inventory levels, production batches, requirements and costs of production per product, and trends in the demand levels. They use all that information in combination with forecasting software in order to define production orders aiming for the most efficient production combinations.
3343.1.7	Supply chain assistant	Supply chain assistants work closely together with managers in the operations processes, namely purchasing, manufacturing, and distribution processes. They help with administrative and pragmatic follow up of actions such as invoicing, drafting and preparation of contracts and purchasing orders, reconciliation of inventory against documents, and communication with distribution channels.

3323.2.3	purchase planner	Purchase planners organise the continuous supply with goods out of existing contracts.
3122.4	Production supervisor	Production supervisors coordinate, plan and direct manufacturing and production processes. They are responsible for reviewing production schedules or orders as well as dealing with staff in these production areas.
1324.3	Logistics and distribution manager	Logistics and distribution managers take decisions on logistic services, operations and provisions. They take internal and external variables into consideration for effective and successful organisational logistic services. They give appropriate support to all the activities of the supply chain from the beginning to the end. These professionals organise the storage and distribution of goods and ensure that the right products are delivered to the right location on time and at a good cost.

- Trends impacts: Driven by numerous Emerging Digital Technologies 4.0 such as IoT, AI, machine learning, Could-Base computing and Big Data analytics are transforming traditional **SCM concepts and tools**.
- Increases sustainability, reduces carbon footprint. AI and real-time data analytics are transforming decision-making in supply chain management, Digital Collaboration Tools …
- Employability: Wide range of demand in aerospace, automotive, energy, and Industry 4.0.

Table 2. SCM employability

COUNTRY	SOURCE	KEY WORD	NUMBER OF OFFERS
France	France Travail. Recherche d'offres - GPAO. France Travail. Retrieved March 12, 2025, from https://candidat.francetravail.fr/offres/recherche?motsCles=GPAO&offresPartenaires=true&range=0-19&rayon=10&tri=0	**GPAO (CAPM): Computer-Aided Production Management**	4186
	France Travail. Recherche d'offres - Responsable d'approvisionnement. France Travail. Retrieved March 12, 2025, from https://candidat.francetravail.fr/offres/recherche?motsCles=Responsable+d%27approvisionnement&offresPartenaires=true&range=0-19&rayon=10&tri=0	**Supply Manager**	5887
	APEC. Recherche d'emploi - Supply Chain. APEC. Retrieved March 18, 2025, from https://www.apec.fr/candidat/recherche-emploi.html/emploi?motsCles=Supply%20Chain&typesConvention=143684&typesConvention=143685&typesConvention=143686&typesConvention=143687&typesConvention=143706&page=0	**Supply Chain**	8633
	LesJeudis. Technicien Supply Chain - Offres d'emploi. LesJeudis. Retrieved March 18, 2025, from https://lesjeudis.com/jobs?title=Technicien+Supply+Chain&page=0&limit=20	**Technicien Supply Chain**	371
Italy	Offerte di lavoro supply chain manager | Adecco	**Supply chain Manager**	578
	Più di 400 annunci per Supply Chain Manager (28 marzo 2025) | Indeed	**Supply chain Manager**	more than 400
	Offerte di lavoro logistica | Adecco	**Logistics**	563
	supply chain Jobs | LinkedIn	**Supply chain**	7793

	supply chain manager Jobs | LinkedIn	**Supply chain Manager**	254
Slovenia	Mojedelo.com	**Transport, purchasing, logistics**	543
	ESS. Iskanje dela. Slovenian Employment Service. Retrieved March 14, 2025, from https://www.ess.gov.si/iskalci-zaposlitve/iskanje-zaposlitve/iskanje-dela/#/?drzava=SI&pokPod=0025,&iskalniTekst=&iskalnaLokacija=	**Mechatronics and logistics**	309
	Careerjet. Delovna mesta - Logistika v Sloveniji. Careerjet. Retrieved March 14, 2025, from https://www.careerjet.si/delovna-mesta?s=logistika&l=Slovenija	**Logistics**	25
	Deloglasnik. Iskanje zaposlitve. Deloglasnik. Retrieved March 18, 2025, from https://www.deloglasnik.si/Iskanje-zaposlitve/?searchWord=&keyword=&job_title=&job_title_id=&area=&category=22	**Warehousing and logistics**	2
Turkey	Kariyer.net (https://www.linkedin.com/jobs/search/?currentJobId=4183257011&keywords=tedarik%20zinciri&location=Turkey&originalSubdomain=tr)	**Supply Chain Specialist**	48
	LinkedIn (https://www.kariyer.net/is-ilanlari?kw=tedarik+zinciri+uzmani)	**Logistics and Supply Chain Manager**	65

- Relevance for the Smart Specialisation Strategy: 11 regions among the 21 French regions consider the SCM activities among the priorities.
- Wide range of applications such as aerospace, automotive, energy, logistics, and Industry 4.0
- Education level: SCM training identified from EQF 4 to 6

Table 3. SCM training examples (extract of the full details available in Annex 2)

Country	Source	Training course description	EQF Level
France	https://maforpro-occitanie.fr/nos-formations/licence-professionnelle-sciences-technologies-sante-mention-metiers-de-l-industrie-conception-et-amelioration-de-processus-et-procedes-industriels-parcours-process-de-fabrication-0	**Licence Pro CAPPI: Vocational Degree in Design and Improvement of Industrial Processes and Procedures:** Trains professionals to enhance production operations while considering standards, quality, costs, and deadlines. Covers new manufacturing technologies like additive manufacturing and their impact on production. Graduates can manage industrial projects, plan activities, and support production optimization in SMEs and large enterprise	6
	https://www.onisep.fr/ressources/univers-formation/formations/post-bac/bts-management-commercial-operationnel	**BTS MCO: Higher National Diploma in Operational Commercial Management:** This program trains operational managers in team management, business administration, and customer relations. Students develop skills in sales, inventory, budgeting, and business intelligence while completing 14 to 16 weeks of internships.	5
	https://joseph-gallieni.mon-ent-occitanie.fr/nos-formations/bac-pro-logistique--29113.htm	**Vocational Baccalaureate in Logistics:** The holder of this baccalaureate in Logistics manages the reception, storage, order preparation, and shipment of goods. They optimize storage and are skilled in operating forklifts. They can also assist in monitoring road transport operations. Their work complies with safety, quality, and environmental regulations. They primarily work in logistics companies, distribution platforms, and corporate logistics services.	4

Slovenia	Mechanical, Traffic, and Woodworking School Nova Gorica School Centre Secondary Vocational and Technical School Bežigrad, Ljubljana	**Mechatronics Technician:** This program combines knowledge of mechanical engineering, electrical engineering, and computer science, including the fundamentals of automation and robotics, which are essential for Industry 4.0.	4
	Higher Vocational School, Ljubljana School Centre (visjasola.sclj.si)	**Logistics Engineer:** This program covers advanced topics in logistics, supply chain management, and process optimization.	5
Germany	https://www.haufe-akademie.de/7867	**Supply Chain Management – Methods and instruments for increasing your added value:** It covers key SCM and logistics concepts through practical exercises. Topics include cost influence, efficiency, customer satisfaction, supply chain structuring, strategy, and the SCOR model. Also addresses inventory strategies, demand forecasting, supplier management, and performance indicators. Focuses on value chain optimization and conflict resolution for practical implementation.	5 & 6
	https://www.haufe-akademie.de/34087	**Basics – Sustainability in Supply Chain Management:** It covers key aspects of building socially, ecologically, and economically sustainable supply chains. Topics include regulatory requirements (Supply Chain Due Diligence Act, EU directives), sustainability measurement, transparency strategies, and integration into business planning. Emphasizes the global impact, competitiveness, and continuous improvement. Includes best practices, case studies, and online resources.	5 & 6
	https://www.haufe-akademie.de/5357	**Strategic Supply Management – Planning and managing logistics networks:** Focuses on designing flexible, market-oriented supply chains in volatile markets. Covers process transparency, cost reduction, and working capital optimization. Key topics include business process integration, procurement, production, logistics strategy, forecasting, inventory management, and distribution optimization. Practical applications involve KPI management, cost control (EVA, target costing), and benchmarking. Includes simulation workshops, best practices, and online learning resources.	6
Italy	https://www.24orebs.com/formazione/professional-master/master-supply-chain-logistica-e-operations	**Supply Chain, Logistics, and Operations :** This program equips professionals with essential supply chain management skills in an increasingly strategic and sustainable field. It covers logistics flow optimization, inventory management, and enterprise resource planning (ERP, MRP). Participants will also explore emerging technologies such as blockchain, IoT, automation, robotics, AI, and machine learning. The curriculum enhances analytical and decision-making abilities, focusing on data analysis, strategic decision-making in complex scenarios, and risk management across the supply chain.	6
	https://www.cegos.it/corsi-formazione/operations/supply-chain-management	**Supply Chain Management:** Business competition is increasingly shifting from a competition between products to a competition between supply chains that drive and direct the distribution and delivery of goods, whether raw materials, semi-finished products, or finished goods. The integrated management of material procurement, production, and product distribution—both within a single company and, more importantly, across its suppliers and customers—is no longer just an opportunity but an urgent necessity. Adopting a holistic end-to-end vision that encompasses multiple companies must inevitably rely on new corporate governance models.	4
Turkey	Istanbul University - AUZEF (Open and Distance Education Faculty)	**Bachelor's Degree in Logistics:** Focuses on supply chain management, inventory control, distribution, and logistics information systems. Graduates can work in managerial positions within logistics companies and production sectors.	6

	Istanbul University - AUZEF	**Associate Degree in Logistics:** Covers fundamental knowledge in storage, transportation, customs procedures, and inventory management. Graduates can work as operators or logistics support personnel.	5
	Ministry of National Education - Vocational and Technical Anatolian High Schools	**Vocational High School Program in Logistics:** Provides practical training in shipment, warehousing, storage, and logistics software. Includes internships in companies. Graduates can work as warehouse supervisors or shipment staff.	4

- Training courses impacts:
  - Emerging Digital Technologies 4.0 are transforming traditional SCM approaches and must therefore be included in training programs.
  - Train students in digital supply chain management, including AI-driven planning and sustainable practices. This prepares workers to manage eco-friendly, data-driven operations
- Added Value for Industrial Processes:
  - New **SCM concepts and tools** addresses at least one criterion in ADMA methodology: Transformation 2: Digital Factory, Digital capabilities, Transparent view on shop floor status, evaluation 4.0
  - Agility, Sustainability, AI driven forecasting, ADMA methodology (Transformation 6: Smart Manufacturing, Manufacturing Planning & Control Processes, evaluation
  - **Modulation:** the topic of **SCM 4.0** is seen as interesting but in the future, not a priority, as currently many SMEs are far from it (see result of the SCM Survey sent to SMEs).

1.2.2. STAGE 2 & 3 - SEARCH AND INFORMATION GATHERING

Stages 2 and 3 involved conducting the literature review and analysis of the field of observation, enabling us to identify the most recent and relevant sources, including scientific and academic papers, industry reports and white papers, standards and regulations, patents and technical documentation, case studies and real-world applications, as well as online articles, blogs, and open-source projects.

All of these sources are indicated in chapters “References”.

1.2.3. ADJUSTMENT & VALIDATION OF THE FIELD OF OBSERVATION

The revised methodology thus applied enabled us to refine and validate the final description of the field of observation: How emerging digital technologies 4.0 and green transition trends impact Supply Chain Management 4.0 (SCM 4.0) concepts and tools, affects SCM activities within industries, market and jobs, VET Centres and learning pathway.

1.2.4. STAGE 4 - COLLABORATIONS AND PARTNERSHIPS

During stages 1 to 3, the main findings were identified, enabling us to validate the scope of the study, move on to stage 4 - collaborations and partnerships - and build two surveys to SMEs and VET Centres.

1.2.4.1. SURVEY ELABORATION

The content of the surveys was reviewed and validated by face-to-face interviews with SME managers and VET centre trainers, and finally by all the LCAMP internal partners involved. The guide lines to build the surveys was to address following points.

Trend Identification and Tracking

- **Objective:** Track the adoption rate of SCM practices within SMEs and understand the urgency or lag in adopting new **SCM concepts and technologies**.
- **Insight for SMEs:** Provides information on where they stand relative to peers in adopting new **SCM concepts and tools**, helping them identify gaps and opportunities.
- **Insight for VETs:** Reveals trending technologies and processes in demand, enabling curriculum adjustments that align with industry needs.

Technology and Process Adoption Levels

- **Objective:** Gauge the level of implementation of key technologies and methods in new **SCM concepts and tools**, such as sensors & IoT, Data analytics and big data, Deep Learning Models …
- **Insight for SMEs:** Enables them to benchmark their progress in adopting new trends and identify where additional investment may be needed.
- **Insight for VETs:** Informs on technology adoption trends, helping to integrate these trends into hands-on training programs and simulations.

Market Shifts and Competitive Positioning

- **Objective:** Understand how new **SCM concepts and tools** are influencing market dynamics, including customer demand, regulatory pressure, and competitive landscape.
- **Insight for SMEs:** Offers perspective on market opportunities in new **SCM concepts and tools**, encouraging strategies to meet new demands or niche markets + adapt SCM processes and Organisation within SMEs
- **Insight for VETs:** Allows VETs to focus on training for competencies linked to emerging market needs, preparing students for areas with high potential.

Challenges and Barriers in Transition

- **Objective:** Identify the primary barriers SMEs face in adopting new **SCM concepts and tools**, such as cost, lack of expertise, or regulatory challenges.
- **Insight for SMEs:** Highlights specific areas where external support (e.g., funding, consulting) could accelerate their transition.
- **Insight for VETs:** Informs where additional educational support might be required, such as training on regulatory compliance or funding application processes.

Assessment of Impact on Jobs and Skills

- **Objective:** Assess how new **SCM concepts and tools** impact existing roles and the emergence of new job functions within manufacturing.
- **Insight for SMEs:** Helps identify which roles will become obsolete or evolve, supporting workforce planning and reskilling efforts.
- **Insight for VETs:** Informs on emerging job profiles, allowing them to update course offerings and training programs to match current job market requirements.

Skills and Competencies Gap Analysis

- **Objective:** Identify the specific skills and competencies that are lacking in the current workforce, both technically and in terms of people, and that are needed to support the development of new **SCM concepts and tools**.
- **Insight for SMEs:** Provides a clear understanding of training needs within the organisation and industry, facilitating targeted upskilling initiatives.

- **Insight for VETs:** Supports curriculum development with a focus on priority skills, whether technical (e.g., data analysis, energy management) or non-technical (e.g., sustainability literacy, problem-solving).

Training Needs and Preferred Learning Modalities

- **Objective:** Discover the types of training SMEs need and the preferred delivery formats, such as online, in-person, or hybrid training options.
- **Insight for SMEs:** Ensures that training options are accessible and practical, supporting their workforce's development in a flexible manner.
- **Insight for VETs:** Allows VET institutions to adjust training formats to the preferences and constraints of SMEs, making programs more accessible and impactful.

Anticipated Future Needs and Emerging Trends

- **Objective:** Gather insights on the future outlook of SMEs regarding new **SCM concepts and tools**, including planned investments, expected technologies, and skill requirements.
- **Insight for SMEs:** Helps businesses align future workforce planning and investment decisions with anticipated market and technological changes.
- **Insight for VETs:** Guides the future evolution of training programs to stay ahead of the industry's needs, ensuring students are trained in the latest competencies and emerging practices.

1.2.4.2. SURVEY EXECUTION

Sample of SMEs and VET Centres consulted the surveys have been addressed to:

- SMEs: our contacts in the organisation (responsible of SCM, Planning, Production execution services or responsible of the company)
- VETs: our contacts in the organisation responsible of learning pathways.

Table 4. Organisations consulted

TARGET AUDIENCE	COUNTRY	NUMBER OF ORGANISATIONS CONSULTED
SME	FR	118
	GER	39
	IT	1
	SI	11
	TR	7
Total SME		**176**
VET	FR	14
	GER	31
	IT	2
	SI	15
	TR	8
Total VET		**70**
Overall Total		**246**

1.2.4.3. ANALYSIS AND RELIABILITY OF THE SURVEY RESULTS

Survey Quality Analysis

- **Aim of the survey:** The survey aims to gather data to understand the current state, challenges and trends in Supply Chain Management (SCM)) for SMEs. It asks specific questions about technologies, implementation strategies, barriers and future developments.
- **Sample selection:** The survey targets companies and VET centres in different sectors and countries (including France, Germany, Italy, Slovenia and Turkey). A non-probability method called 'convenience sampling (Suen Lee-Jen Wu et al., 2014) is used, as the sample is targeted and focused.
- **Methodology**: The survey is based on an extensive literature review on state of the art in new **SCM concepts and tools**. It is designed as a cross-sectional study, collecting data at a specific point in time. The survey contains mostly closed questions (e.g. multiple choice, Likert scales) and only a few open questions.

Results and findings:

- **Technologies and implementation strategies:** The survey documents the current state of SCM processes and their implementation in various industries.
- **Challenges**: Identifies key challenges in implementing new **SCM concepts and tools**.
- **Future developments**: The survey provides insights into future developments and training needs to address the expected skills gaps.

Categorisation:

- **Descriptive survey** (Silva, 2008): Documents trends, challenges and status quo in SCM processes.
- Non-probability method: Convenience sampling, no evidence of random or stratified sampling.
- **Cross-sectional study** (Hemmerich, n.d.): One-time data collection without iterative processes or long observation periods.
- **Quantitative**: Closed-ended questions with structured, numerically evaluable data.

Recommendations:

- To improve the validity of the survey and minimise bias, adjustments could be made, such as the introduction of probabilistic sampling methods.

Survey Representativeness Analysis

Assumption:

- Selected companies with a direct link to the topic, who are professionally and factually recognised, support us without reservation in providing high quality responses to our surveys. This also applies to the training centres.

Execution:

- The response rate has shown that it is very difficult to get responses to such surveys. In the end, cold calling had to be used to obtain survey results.

Theoretical evaluation of results:

- The response rate to a survey varies according to a number of factors, including the target population, the distribution channel and the design of the questionnaire. For internal surveys, such as those carried out among a company's employees, the average response rate is generally between 30% and 40%. On the other hand, external surveys, aimed at external audiences, have lower average response rates, often between 10% and 13%. (Bhat, 2018; hubspot, 2023)

- In the specific context of manufacturers and training centres, response rates can vary depending on the commitment of respondents and the perceived relevance of the survey. For example, one study showed that customer satisfaction surveys generally achieve a response rate of 33%, although this figure varies according to the perceived value to the respondent. (Bhat, 2018)
- It is important to note that the length and complexity of the questionnaire also influences the response rate. Surveys with fewer than 12 questions have an average response rate of 83%, while longer surveys may have a lower response rate.(Le Sphinx, 2024)

1.2.5. STAGE 6 - REPORT VALIDATION

The report has been validated by experts during a collaboration meeting.

2. SCM – SCOPE & DEFINITIONS

Supply Chain Management (SCM) coordinates the flow of goods, information, and finances from raw material acquisition to final product delivery. It integrates procurement, production, distribution, and logistics to **enhance efficiency and reduce costs**. SCM ensures value creation by delivering the right products **to the right place, at the right time, and in the right condition** (Chopra & Meindl, 2007; kiwop, 2021).

Supply Chain Planning is based on 5 Levels of Time Horizon and Complexity Hierarchy sum-up in the following graph; understanding these SCM's **planning horizons** is essential for effective coordination and optimization (Dr. Muddassir Ahmed, 2016).

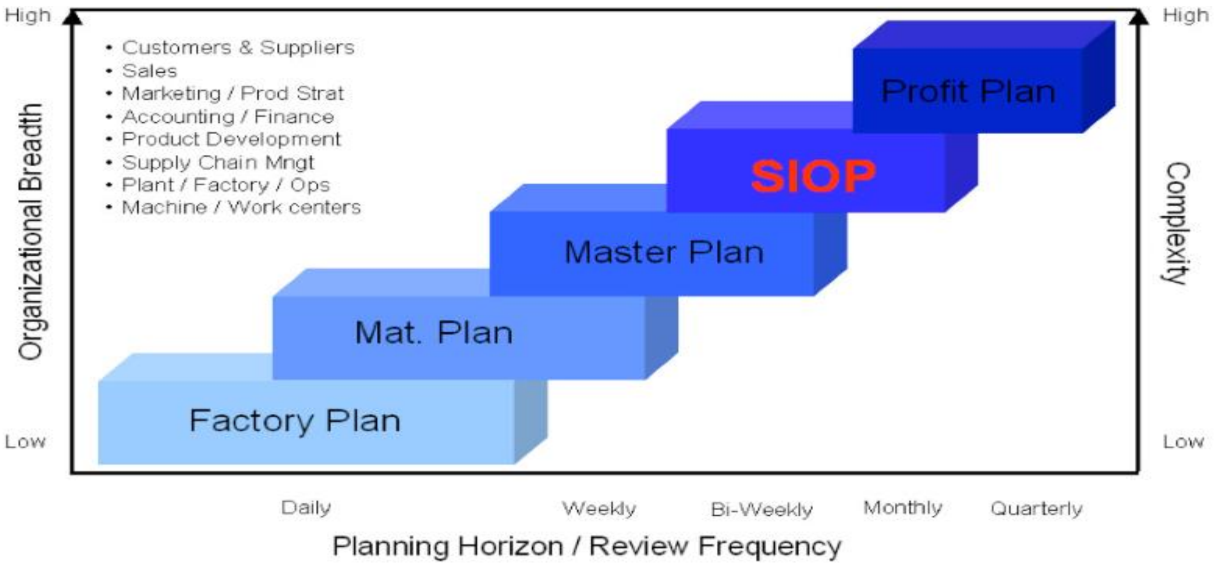

Figure 2. Supply Chain Planning - 5 Levels of Time Horizon and Complexity Hierarchy (Dr. Muddassir Ahmed, 2016)

These 5 levels can be grouped as follow (Vinay Rajani, Preeti AryaCrossman, 2023):

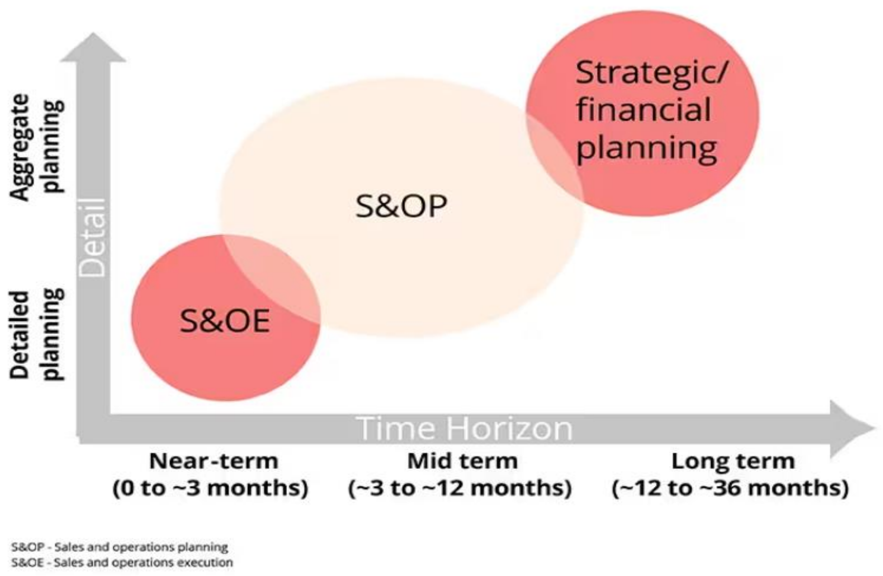

Figure 3. Planning along two dimensions - detail and time horizon (Vinay Rajani, Preeti AryaCrossman, 2023)

These definitions are sum-up in the following table:

Table 5. S&OP vs S&OE - Execution level

Planning Layer	Process/Method	Purpose
Profit Plan (Financial & Strategic)	**Profit-Driven Supply Chain Optimization**	Aligns supply chain decisions with **financial goals**, maximizing profitability, ROI, and cash flow. Utilizes advanced analytics for cost-to-serve models, pricing strategies, and revenue growth.
S&OP (Strategic & Tactical)	**Master Production Schedule (MPS)**	Converts demand forecasts into a **high-level production plan**, typically for a few months.
S&OE (Operational & Execution)	**Material Requirements Planning (MRP)**	Breaks down MPS into **specific material and component needs** for production.
	Factory Floor Scheduling: Finite Capacity Scheduling (FCS) / Infinite Capacity Scheduling (ICS)	**FCS:** Creates **realistic**, resource-constrained production schedules. **ICS:** Assumes unlimited capacity but requires manual adjustments for execution feasibility.

- The **Profit Plan or Strategic/financial planning** is the **highest level of Supply Chain Planning**, extending up to **12 months** and typically reviewed **quarterly**. It serves as a **financial planning foundation**, allowing businesses to anticipate **investment needs** in areas such as **receivables, inventory, new product launches, workforce expansion, capital investments, and facilities.** (Dr. Muddassir Ahmed, 2016).
- **S&OP** is the **strategic and tactical planning process**, typically conducted monthly or quarterly, that aligns demand forecasts with production capacity and financial objectives. It ensures that medium-to-long-term production and supply chain strategies are in place. **The Master Production Schedule (MPS)** is a key output of S&OP, converting high-level plans into a **detailed production roadmap** of finished goods for the coming months. It outlines what needs to be produced, when, and in what quantities, typically driven by customer orders and forecasts. (Takyar, 2024).
- **S&OE**, on the other hand, operates on a **short-term horizon** (daily to weekly) to adapt production and supply chain execution to real-world variability. It bridges the gap between S&OP and real-time production by refining schedules based on actual demand, material availability, and operational constraints.
    - **Material Requirements Planning (MRP II)** supports S&OE by translating MPS into precise **component and raw material requirements**, ensuring that production processes receive the necessary inputs on time. MRP II uses inventory data, production order and bill of materials (BOM) data to calculate the quantity and timing of purchases of additional incoming goods (Siemens, n.d.-b).
    - At the **execution level**, **Finite Capacity Scheduling (FCS)** and **Infinite Capacity Scheduling (ICS)** dictate how manufacturing resources are allocated.
        - **Finite Capacity Scheduling (FCS):** This approach acknowledges the actual limitations of resources - such as machinery, labor, and materials - when planning production. It ensures that operations are scheduled only when the necessary resources are available, thereby creating realistic and executable production schedules. This method helps prevent overloading resources and minimizes

bottlenecks in the production process (Everhour Blog - Maria, 2025; PlanetTogether, 2019).

- **Infinite Capacity Scheduling:** In contrast, infinite capacity scheduling assumes that unlimited resources are available for production. It schedules operations based solely on demand and lead times, without considering current resource availability. While this can simplify initial planning, it often leads to resource overloads and unrealistic production schedules, as it doesn't account for existing workloads or capacity constraints. (Everhour Blog - Maria, 2025; Sapot, 2021).
- **Infinite capacity scheduling** is quicker to set up with less data accuracy but requires significant manual effort afterward to adjust workloads and avoid overcommitment. **Finite capacity scheduling** ensures an executable schedule upfront by carefully managing resource constraints, but it demands meticulous data setup in the ERP system. The choice depends on whether you prefer **pre-scheduling precision or post-scheduling corrections**.

By integrating **Profit plan, S&OP, S&OE, MPS, MRP, FCS, and ICS**, SCM ensures a **balanced, responsive, and efficient** supply chain that can adapt to both strategic goals and operational realities.

3. SCM – CONTEXT

In 2025, **Supply Chain Management (SCM)** continues to face a rapidly changing global landscape. The increasing complexity of international markets, coupled with shifting customer expectations, geopolitical uncertainties, and evolving regulatory frameworks, poses significant challenges for businesses striving to maintain competitive supply chains. At the same time, the global push towards sustainability and the **green transition** introduces additional pressure on companies to adopt environmentally friendly practices while optimizing efficiency.

Emerging **digital technologies** have been identified as a key to addressing many of these challenges. Technologies such as **Artificial Intelligence (AI)**, **IoT**, **machine learning**, and **blockchain** are poised to revolutionize SCM, offering new ways to enhance visibility, streamline operations, and improve decision-making. These innovations promise to improve supply chain agility, reduce costs, and drive better demand forecasting, ultimately helping organisations meet the evolving needs of their customers and markets.

Furthermore, the **green transition** remains a central objective in the business world, as organisations must align their supply chain strategies with **sustainability goals**. From reducing carbon footprints to embracing circular economy principles, SCM must evolve to integrate more sustainable practices without compromising operational performance. Digital tools offer exciting opportunities to align SCM with green transition goals, such as improving energy efficiency, optimizing waste management, and enhancing sustainable sourcing.

This chapter will explore the **international context** of SCM in 2025, examining the global forces that are shaping its future. It will also delve into the promising role of **emerging technologies** in transforming SCM, with a particular focus on their potential to meet the **green transition objectives** that are becoming increasingly crucial to the industry's success. By understanding these dynamics, businesses can better navigate the challenges ahead and leverage digital advancements to create more resilient, efficient, and sustainable supply chains.

3.1. GLOBAL ECONOMIC AND GEOPOLITICAL CHALLENGES

The **global supply chain** has faced **significant disruptions** in recent years, requiring companies to **adapt and innovate** to maintain operational efficiency and customer satisfaction.

3.1.1. SUPPLY CHAIN CHALLENGES (2021–2022)

During 2021 and 2022, global supply chains were severely disrupted by port congestion, labor shortages, manufacturing delays, and extreme weather events, exacerbating logistical challenges. The ongoing impact of COVID-19 variants, factory shutdowns, and major incidents like the **Ever Given** blockage in the Suez Canal further strained operations.

In response, businesses adapted by shifting to backorder sales models, prioritizing domestic suppliers to reduce delays, and optimizing efficiency to navigate unprecedented volatility (Extensiv, 2025).

3.1.2. SUPPLY CHAIN CHALLENGES (2023–2024)

Between 2022 and 2023, global supply chains faced mounting challenges as **geopolitical tensions**, including the **Ukraine conflict** and **Middle East instability**, forced companies to reroute shipments and avoid critical trade routes like the **Suez Canal**. At the same time, **climate-related disruptions**, such as extreme temperatures and hurricanes, further strained global freight and production. **Rising inflation** drove up costs for raw materials, energy, and logistics, intensifying financial pressures. In response, businesses strengthened logistics partnerships, accelerated nearshoring efforts, and optimized cost structures to maintain profitability amid ongoing volatility (Extensiv, 2025).

3.1.3. GLOBAL ECONOMIC AND GEOPOLITICAL CHALLENGES IN 2025

In 2025 the international trade landscape is marked by increasing protectionism and evolving trade policies compelling businesses to seek alternative sourcing and manufacturing options. Companies are exploring logistics solutions to navigate these challenges effectively (Inagaki et al., 2025; Vartabedian, 2025).

Below is an **overview** of the top supply chain challenges in 2025, analysed by (Extensiv, 2025; Matt Stekier, 2025; Uma Mahesh, 2024)

- **Global Economic Disruptions**: Supply chains are affected by shifts in trade policies, economic instability, rising costs, and trade agreements (e.g., Brexit), leading companies to reconsider sourcing strategies and financial planning.
- **Reshoring & Nearshoring**: Companies are relocating production closer to home to reduce risks and costs, though high setup costs and talent shortages present challenges.
- **Supply Chain Resilience & Agility**: To improve adaptability, businesses are adopting flexible strategies such as collaborative planning, supplier diversification, and real-time risk monitoring, but inventory management remains difficult due to demand volatility and inconsistent suppliers.
- **Labor Shortages & Workforce Development**: **Ongoing skill shortages** in trucking, warehousing, and logistics planning are **slowing operations**, with **an** aging workforce adding further strain.

- **Cybersecurity Threats**: Increased digitalization of supply chains introduces rising cybersecurity risks, including ransomware attacks, requiring investment in stronger cybersecurity infrastructure.
- **Technological Failures**: Despite the benefits of AI, IoT, and machine learning, companies face risks of technological failures, including system malfunctions and software bugs, necessitating rigorous testing and fail-safes.

3.1.4. HOW TO OVERCOME SUPPLY CHAIN ISSUES IN 2025

Despite **ongoing disruptions**, **supply chains** present opportunities. To address the key challenges in Supply Chain Management (SCM) in 2025, recent articles like (KPMG, 2024; Pullen, 2025; Uma Mahesh, 2024) explain that businesses must leverage emerging technologies and implement strategies that enhance resilience, operational efficiency, and sustainability. Below is a summary of the key solutions:

- **Adoption of Digital Supply Networks (DSNs):**
  Traditional supply chains often suffer from fragmentation, which leads to inefficiencies. **Digital Supply Networks** integrate advanced technologies like **AI**, **IoT**, and **blockchain** to create real-time, interconnected ecosystems that enable data-driven decision-making. This approach enhances visibility and improves supply chain coordination, ultimately making businesses more resilient and adaptable to disruptions.
- **Integration of Advanced Technologies:**
  AI and **machine learning** are transforming SCM by improving **inventory management**, **predictive analysis**, and **route optimization**. These technologies help organisations anticipate disruptions, optimize supply chains proactively, and make better-informed decisions. Similarly, **IoT** provides real-time tracking of goods and assets, ensuring greater visibility, while **blockchain** ensures transparency and trust by enhancing the security of transactions within the supply chain.
- **Emphasis on Supply Chain Resilience:**
  Advanced technologies, particularly **AI** and **predictive analytics**, enable supply chains to respond quickly to changes in market trends and demand shifts. By integrating tools for **route optimization**, companies can reduce costs, lower fuel consumption, and minimize emissions, all while enhancing compliance with evolving regulations.
- **Sustainability and Circular Supply Chains:**
  As part of the **green transition**, businesses are increasingly adopting **circular supply chains** to minimize waste and emissions. **AI** and **IoT** play a critical role in tracking reusable materials and ensuring ethical sourcing. Organisations that prioritize **sustainable sourcing**, energy-efficient logistics, and the circular economy not only meet regulatory requirements but also enhance their reputation and meet consumer expectations.
- **The Role of Data Management:**
  Effective data management is central to modern SCM. Fragmented or poor-quality data can hinder decision-making. Organisations must focus on ensuring data **availability**, **consistency**, and **reliability**. A use-case driven approach to data management, complemented by ongoing improvements, ensures that supply chains can adapt to disruptions while optimizing performance.
- **Low-Code Platforms for Enhanced Agility:**
  Low-code platforms enable businesses to automate processes and connect disparate systems quickly, reducing development time and improving agility. These platforms empower business users, even those with limited technical expertise, to create and deploy applications that support responsive and adaptive supply chains.
- **Focus on Scope 3 Emissions:**
  With increasing regulatory pressure to address **Scope 3 emissions** (those generated throughout the supply chain), companies are adopting **digital platforms** to gather and

integrate emissions data from suppliers. This data is crucial for building accurate emissions baselines and ensuring compliance with environmental goals.

- **Workforce Upskilling & Digital Readiness**: As **supply chains integrate AI, IoT, and automation**, businesses must **train employees to adopt and manage new technologies effectively**. A culture of **continuous learning and upskilling** is essential to **bridge the digital skills gap, enhance operational efficiency, and ensure seamless technology implementation**. Organisations should **designate tech-savvy employees to test new systems, lead training, and support digital transformation efforts**

In sum-up, in order to **navigate supply chain challenges**, companies must **invest in supply chain agility, digital security, workforce training, and sustainability efforts**. **AI, automation, and predictive analytics** will play a critical role in **enhancing resilience and efficiency.**

3.2. SOFTWARE AND AI MARKET IN SUPPLY CHAIN

The following statistics (Statista, 2024a, 2024b, 2024c) on the evolution of the market show that supply chain management (SCM) software market is promising in growth and job opportunities. In Europe, the SCM software market is expected to reach US$4.70 billion by 2025, with a compound annual growth rate of 3.26% between 2025 and 2029. In the G7 countries, the market is expected to be even larger, reaching US$15.40 billion, with a compound annual growth rate of 3.62%. Germany is positioning itself as a leading market for SCM software, as German companies increasingly turn to digital solutions to improve the efficiency of their supply chains. This development points to an increasing demand for skilled workers in the SCM sector, which has a positive impact on employability and job opportunities in the sector.

Analysis of the two market segments - artificial intelligence (AI) in the supply chain and supply chain management (SCM) software - reveals a clear interrelationship and convergent growth dynamic within the digital transformation of global supply chains.

Artificial Intelligence (AI) in the Supply Chain highlights the increasing integration of AI technologies into supply chain processes. The projected increase in market volume from USD 9.15 billion in 2024 to USD 40.53 billion in 2030 (CAGR: 28.2%) reflects a profound need for data-driven, automated and resilient supply chains. In particular, the COVID-19 pandemic has increased the importance of risk management through AI, highlighting the role of intelligent systems in predicting and responding to supply chain disruptions (MarketsandMarkets, 2025).

Table 6. Scope of the study

Report Attribute	Details
Estimated Market Size	USD 9.15 billion
Projected Market Size	USD 40.53 billion
Growth Rate	CAGR of 28.2%
Market size available for years	2020–2030
Base year considered	2023
Forecast period	2024–2030
Forecast units	USD Million/USD Billion
Segments Covered	Involves intelligent technologies development, deployment and usage to optimize and automate key industrial processes. Tools like machine learning, predictive analytics real-time data processing.

Regions covered	North America, Europe, Asia Pacific, and Rest of the World

Supply chain management (SCM) software also shows the continued growth of the SCM software market, particularly in economically strong regions such as Europe and the G7 countries. The projected market volume of USD 15.4 billion in the G7 by 2029, at a solid CAGR of 3.62%, points to an increasing demand for digital solutions - including AI-based applications.

This is because modern SCM software solutions are increasingly integrating AI components to enable predictive analysis, automated decision making and dynamic optimisation. The expansion of the market for AI in the supply chain, as described in Artificial Intelligence (AI) in the Supply Chain, is thus a key driver for the functional development and attractiveness of SCM software solutions, as described in Supply Chain Management (SCM) Software.

In addition, this technological convergence is not only transforming systems but also impacting the labour market: The increasing demand for AI-integrated SCM software is driving the need for professionals with interdisciplinary skills, particularly in data science, AI, logistics and process management.

The growth drivers of AI in the supply chain not only fuel the technological development of the SCM software market but also increase the demand for specialised professionals. Conversely, the SCM software market provides the commercial platform for implementing and scaling AI applications. A self-reinforcing cycle of innovation is emerging between technology development and market needs - with significant implications for the economy, employment and competitiveness.

4. DIGITAL SOLUTIONS FOR SCM 4.0

Industry 4.0 technologies - such as **Artificial Intelligence (AI), Machine Learning (ML), IoT, Blockchain, and Edge and Cloud Computing** - are revolutionizing **Supply Chain Management (SCM) and Profit Planning (PP)** by **enhancing forecasting, optimizing resource allocation, and automating decision-making**.

Below are key insights into impact of these technologies.

4.1. EDGE VS CLOUD-BASED COMPUTING

4.1.1. WHAT IS EDGE COMPUTING?

Edge computing is a decentralized approach to data processing where computation occurs **closer to the source of data generation**, reducing latency and bandwidth usage. This contrasts with traditional cloud computing, where data must be sent to centralized data centres for processing.

4.1.2. HOW EDGE COMPUTING TRANSFORMS SCM

- **Faster Real-Time Decision-Making**
  - Edge computing **reduces the time needed** to analyse supply chain data by processing it **locally** at distribution centres, warehouses, and transportation hubs.
  - **Example: Maersk** utilizes edge computing to analyse data in near real-time, enabling swift responses to supply chain demands(Paula Rooney, 2022)

- **Resilient Supply Chain Operations**
    - Edge computing ensures **business continuity** even when cloud access is disrupted.
    - **Example:** For instance, in retail environments, edge computing allows for real-time monitoring of inventory levels and shipment tracking. This local data processing enables immediate responses to issues, minimizing disruptions and maintaining seamless operations (Uchechukwu Christopher Anozie et al., 2024).

- **Enhanced Security & Data Privacy**
    - Since **critical supply chain data is processed locally**, edge computing **reduces the risks associated with transmitting sensitive information** over the internet.
    - **Example: Attabotics** uses edge computing to enhance security in its automated storage and retrieval systems, minimizing data transmission risks ('Attabotics', 2025)

- **Reduced Cloud Computing Costs**
    - By processing data locally, **less bandwidth and cloud storage are needed**, lowering **operational costs** for SCM firms.
    - **Example: DHL** integrates edge computing to optimize resource allocation, reducing reliance on centralized cloud services (*Edge Computing*, n.d.).

4.1.3. CLOUD-BASED COMPUTING?

At the same time, the recent articles (George Maksimenko, 2024; Ruchundre Reid, 2024) mention that Cloud-based computing is transforming **Supply Chain Management (SCM)** by **enhancing efficiency, scalability, and real-time collaboration** across global networks.

- **Adoption Trends**: Businesses are increasingly migrating to cloud platforms to leverage scalable computing resources and reduce IT infrastructure costs.
- **Integrated Planning:** Cloud-based solutions facilitate collaboration across departments, ensuring that sales, operations, and finance are aligned with strategic goals. (Whitney Gillespie, 2024).
- **AI Integration**: Cloud computing is essential for deploying AI services, providing the necessary infrastructure for data storage and processing.
- **Security Enhancements**: Advancements in cloud security measures are addressing concerns related to data privacy and compliance, encouraging broader adoption across regulated industries

4.2. INTERNET OF THINGS (IOT) IN SCM 4.0

IoT devices enable real-time tracking and monitoring environmental conditions of goods during transit, ensuring product quality and compliance. Supply Chain Digital Twins simulates production processes to optimize operations, improve quality control, and minimize waste (Navin Kumar Parthiban, 2023; Pullen, 2025).

4.2.1. HOW IOT TRANSFORMS INVENTORY MANAGEMENT

- **Real-Time Stock Visibility**
    - IoT-enabled **RFID tags, beacons, and sensors** track inventory levels in real-time.
    - **Example: Walmart** utilizes IoT-powered smart shelves that notify managers when restocking is needed (Joaquim Cervera, 2024).

- **Automated Replenishment**

- AI analyses IoT-generated inventory data to trigger **automatic restocking** based on demand predictions.
- **Example: Amazon's** fulfillment centres use IoT to automate order processing and reduce out-of-stock incidents .

- **Supply Chain Condition Monitoring**
  - IoT sensors **track temperature, humidity, and shock exposure** for sensitive shipments (e.g., pharmaceuticals, food supply chains).
  - **Example: Cold chain logistics companies** use IoT devices to maintain optimal storage conditions during transit (Elpro, n.d.).

- **IoT & Edge Computing for Smart Warehouses**
  - IoT devices **integrated with edge computing** enable **automated sorting, picking, and warehouse mapping** for optimal efficiency.
  - **Example: DHL's Smart Warehouse** uses IoT-based automation robots for order fulfilment (DHL, 2024).

4.2.2. OPC UA: A SECURE AND INTEROPERABLE FRAMEWORK FOR INDUSTRIAL IOT

To fully realize the potential of IoT in Supply Chain Management (SCM), robust and standardized communication protocols are essential. **OPC UA (Open Platform Communications Unified Architecture)** has emerged as a key standard for secure, platform-independent, and scalable industrial communication. Originally developed by the OPC Foundation, OPC UA enables seamless data exchange between machines, systems, and applications in smart factories and logistics environments (Agathe Lecomte, 2025; OPC Foundation, 2012).

Relevance to SCM:

- **Interoperability**: Facilitates data integration across diverse equipment and software in production and logistics.
- **Security**: Incorporates encryption, authentication, and auditing, making it suitable for secure data exchange in digital supply chains.
- **Scalability**: Supports horizontal (machine-to-machine) and vertical (sensor-to-cloud) integration, aligning with SCM needs for real-time monitoring and control.
- **Information Modeling**: OPC UA's information modeling capability allows standard and custom data models, supporting the digital twin and predictive analytics initiatives.

As SCM 4.0 increasingly relies on connected devices and real-time data, **OPC UA serves as a foundational technology** enabling smart, secure, and interoperable supply chains.

4.3. AI, ROBOTICS AND AUTOMATION IN SCM 4.0

Artificial Intelligence (AI) is revolutionizing **robotics and automation** in **Supply Chain Management (SCM)** by increasing **efficiency, accuracy, and adaptability** across logistics, warehousing, and production.

Warehouse Automation: Companies like Amazon are increasingly integrating robotics into warehouse operations to boost efficiency and reduce delivery times. This shift towards automation is helping Amazon cut costs, with new robotic warehouses potentially saving the company $10 billion annually by 2030 (Uddin, 2025).

AI-driven software **analyses massive amounts of supply chain data** to improve forecasting, decision-making, and operational efficiency.

Example of Amazon:

- The integration of robotics and AI has led to significant savings, with projections estimating annual reductions of $10 billion by 2030 (Krause, 2024).
- Improved efficiency and faster delivery times have bolstered customer satisfaction, reinforcing Amazon's market position.

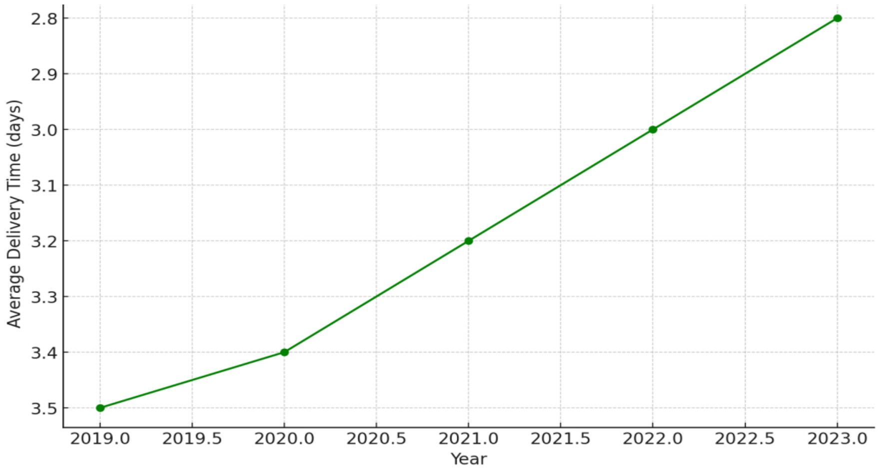

Figure 4. Impact of AI on Amazon's Delivery speed – Source: Carsten Krause, CDO TIMES Research & Amazon (Krause, 2024)

4.4. CYBERSECURITY & BLOCKCHAIN TECHNOLOGY IN SCM 4.0

The integration of digital technologies - such as Artificial Intelligence (AI), the Internet of Things (IoT), cloud computing, and blockchain - has significantly transformed Supply Chain Management (SCM), improving operational efficiency, end-to-end visibility, and real-time decision-making. However, this digital evolution also introduces new cybersecurity risks, requiring organisations to safeguard systems, data, and transactions to preserve trust and resilience.

Among these technologies, **blockchain stands out as a specific and strategic enabler**, particularly in addressing security and traceability challenges. Unlike other technologies, blockchain creates a **decentralized and immutable ledger** of transactions, ensuring that all participants across the supply chain can access **trusted, tamper-proof data**. Its ability to guarantee data integrity and transparency makes it especially valuable in complex, multi-stakeholder supply networks (Sarah Shelley, 2024).

4.4.1. CYBERSECURITY IMPLICATIONS IN DIGITALIZED SUPPLY CHAINS

As supply chains become more interconnected through digital technologies, they face increased exposure to cyber threats. Key concerns include:

- **Advanced Persistent Threats (APTs):** Sophisticated, prolonged cyberattacks targeting sensitive information within supply chains.

- **Supply Chain Poisoning:** The deliberate introduction of vulnerabilities or malicious components into supply chain processes, potentially compromising the integrity of products or services.
- **Data Breaches:** Unauthorized access to confidential data, leading to financial losses and reputational damage.

4.4.2. PREVALENT CYBER THREATS IN DIGITAL SUPPLY CHAINS:

The convergence of AI, IoT, cloud computing, and blockchain in SCM introduces specific vulnerabilities:

- **IoT Vulnerabilities:** The widespread adoption of IoT devices expands the attack surface, making supply chains susceptible to cyberattacks that can disrupt operations.
- **Cloud Computing Risks:** While cloud services offer scalability and efficiency, they also present challenges related to data security and compliance, especially when third-party vendors are involved.
- **Blockchain Security Issues:** Despite blockchain's promise of enhanced security through decentralization, it is not immune to threats such as attacks on smart contracts and privacy concerns (Alajlan et al., 2023).

4.4.3. BEST PRACTICES TO MITIGATE CYBERSECURITY RISKS

To safeguard digital supply chains, organisations should implement the following strategies:

- **Integrated Security Frameworks:** Adopt coordinated cybersecurity measures that ensure resilience across complex IoT-based supply chains (Masip-Bruin et al., 2021).
- **Enhanced Visibility:** Utilize advanced technologies to gain real-time insights into supply chain activities, enabling prompt identification and response to potential threats (IBM, 2024).
- **Vendor Risk Management:** Establish stringent security protocols for third-party vendors to prevent breaches originating from external partners.
- **Continuous Monitoring:** Implement ongoing surveillance of network activities to detect and address anomalies before they escalate into significant security incidents.

By proactively addressing these cybersecurity challenges, organisations can fully leverage the benefits of digital technologies in SCM while protecting their operations and maintaining stakeholder trust.

4.5. AI-DRIVEN TECHNIQUES IN SCM 4.0 TOOLS

The integration of **AI, IoT, cloud computing, and blockchain** is transforming supply chains into **intelligent, data-driven ecosystems**. These technologies collectively enhance **analytics and operational efficiency**, enabling businesses to respond swiftly to market dynamics.

AI processes vast amounts of real-time data, generating **actionable insights** that allow manufacturers to adapt rapidly to changing conditions (Deskera, 2023; PlanetTogether, 2024; Rootstock Software, 2024). By optimizing workflows, improving decision-making, and providing **real-time visibility**, AI is revolutionizing supply chain management. Additionally, AI-driven solutions **predict potential disruptions and prescribe proactive strategies**, helping businesses mitigate risks effectively (Sarah Shelley, 2024).

The following chapter detail how SCM is being transformed by a suite of AI and data-driven technologies, including Machine Learning (ML), Deep Learning, Natural Language Processing (NLP), and advanced optimisation algorithms.

- ML models like Decision Trees and SVMs enhance forecasting, procurement, and planning,
- Neural networks and Transformers (e.g. LSTMs, BERT, GPT) are revolutionizing predictive scheduling and unstructured data analysis.
- Optimization techniques such as Genetic Algorithms and Particle Swarm Optimization improve resource allocation and production flow in complex, dynamic environments.
- NLP adds a layer of intelligence by extracting actionable insights from textual data, supporting risk identification and operational decision-making.
- To ensure transparency and trust in AI-powered systems, Explainable AI (XAI) and Interpretable Machine Learning (iML) are becoming essential, enabling human-centric, reliable, and adaptable decision-making across the supply chain.

4.5.1. MACHINE LEARNING (ML)

Machine Learning (ML) is the foundation of **modern supply chain automation**, improving **forecasting accuracy, procurement decisions, financial planning, and production scheduling**.

By recognizing demand patterns, optimizing procurement, and dynamically adjusting schedules, ML significantly enhances supply chain responsiveness.

Machine learning algorithms **predict demand fluctuations, optimize procurement schedules, and reduce material shortages** by analysing past inventory movements and production data.

4.5.1.1. DECISION TREES AND RANDOM FORESTS

Description (Random Forests, 2023; Sruthi, 2021)

- **Decision Trees:** These are tree-like models used for decision-making. They split data into subsets based on feature values, creating a hierarchy of decisions that lead to a final outcome. Each node represents a decision based on a feature, and branches represent possible outcomes. **AI-driven Decision Trees** analyse **historical inventory usage, supplier lead times, and production trends** to optimize material orders.
- **Random Forests** is an ensemble learning method that builds multiple decision trees and merges their results to improve accuracy and control over-fitting. It aggregates the predictions from individual trees to make a final decision, enhancing robustness and reliability. They improve **supply stability** by considering multiple procurement scenarios and identifying risk factors.

4.5.1.2. SUPPORT VECTOR MACHINES (SVM)

This supervised learning model is used for classification and regression tasks. It works by finding the hyperplane that best separates data into different classes. SVM is effective in high-dimensional spaces and is used for tasks like demand forecasting and inventory classification (Jang, 2025).

4.5.1.3. PROS:

- **Increases forecasting accuracy** for supply chain and financial planning.
- **Reduces costs** by optimizing procurement and scheduling.
- **Automates resource allocation**, saving time and reducing errors.
- **Interpretable models** for financial and supply chain optimization.

- **Accurate in predicting supply chain fluctuations**
- High **accuracy** in predicting supply and demand risks.

4.5.1.4. CONS:

- Requires large datasets for training ((Vaswani et al., 2023).
- Computationally intensive (T. Chen & Guestrin, 2016).
- Can overfit when dealing with **too many variables** (T. Chen & Guestrin, 2016).

4.5.2. DEEP LEARNING - NEURAL NETWORKS FOR PRÉDICTIVE SCHEDULING

Neural Networks **model complex supply chain and financial data**, improving time-series forecasting

Subset of Machine Learning, Neural networks and particularly Recurrent Neural Networks (RNNs) and Transformer models, are essential for predictive scheduling in supply chain management.

RNNs & LSTMs predict **future sales, production demand, and financial performance**

4.5.2.1. RECURRENT NEURAL NETWORKS (RNNS) & LONG SHORT-TERM MEMORY (LSTM) NETWORKS

Description:

- **RNNs**: These neural networks are designed to process sequential data, making them suitable for time-series forecasting. They maintain a form of memory that allows them to consider previous inputs when making predictions (Gołąbek et al., 2020).
- **LSTMs:** A type of RNN that can learn long-term dependencies. They are particularly effective in modeling time-series data, such as production cycles, by retaining information over extended sequences.

4.5.2.2. TRANSFORMER MODELS FOR DYNAMIC SCHEDULING

Description:

- **Transformer Models:** These models, such as BERT and GPT, process large datasets and detect real-time scheduling anomalies. They are particularly effective in handling long-range dependencies in data, making them suitable for dynamic scheduling adjustments (Vaswani et al., 2023).
  These Transformer Models are foundational to the development of LLMs (Large Language Models). These models excel in processing large datasets and detecting real-time scheduling anomalies. Their ability to handle long-range dependencies in data makes them ideal for Forecast Management and dynamic scheduling adjustments for instance. LLMs can analyse unstructured data, such as supplier communications and market reports, to provide insights that enhance decision-making processes (Vinay Rajani & Preeti AryaCrossman, 2023).

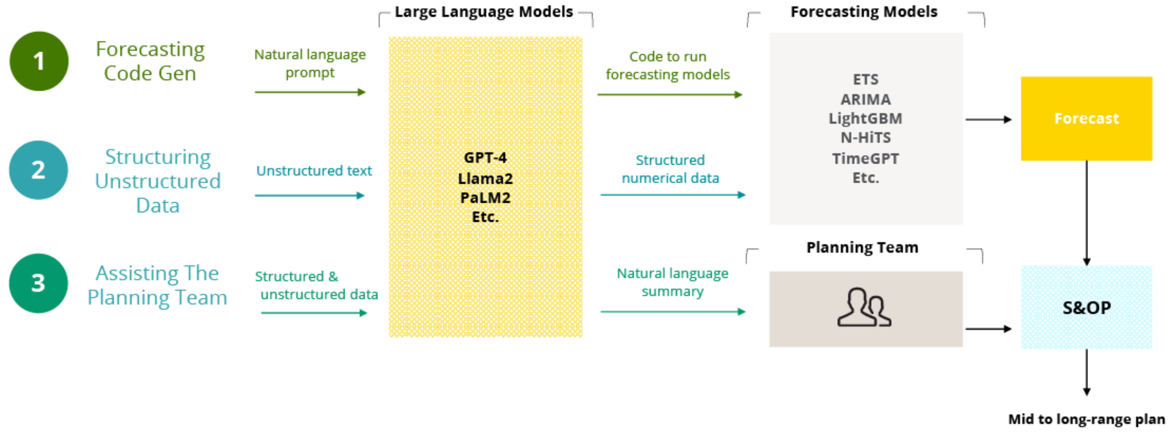

Figure 5. How LLMs Support Better Forecasting & Planning processes (Vinay Rajani & Preeti AryaCrossman, 2023)

4.5.2.3. PROS:

- **Highly effective** for financial and operational forecasting.
- Transformer models, including LLMs like BERT and GPT, can process vast amounts of data efficiently. They excel in handling unstructured data, such as text from supplier communications and market reports, which is crucial for comprehensive analysis.
- These models can detect scheduling anomalies in real-time, allowing for quick adjustments and minimizing disruptions in the supply chain.

- LMs can understand context and nuances in textual data, providing more insightful predictions and analyses compared to traditional models.
- By analyzing unstructured data, LLMs can provide valuable insights that enhance decision-making processes, leading to more informed and strategic choices.

4.5.2.4. CONS:

- **Transformer models and LLMs** require significant **computational resources** for training and inference, which can be costly and resource-intensive (Lam et al., 2024).
- The performance of LLMs heavily relies on the quality of input data. Inconsistencies or biases in the data can lead to inaccurate predictions and decisions.
- Integrating LLMs into existing SCM systems can be complex and may require significant adjustments to workflows and infrastructure.
- **While LLMs** provide powerful insights, their decision-making processes can be opaque, making it difficult for stakeholders to understand and trust the outputs without explainability techniques.
- Implementing and maintaining LLMs demand skilled personnel and continuous monitoring, which can impact the overall return on investment.

4.5.3. CLUSTERING ALGORITHMS FOR OPTIMIZATION

4.5.3.1. K-MEANS

K-Means clustering is a widely used unsupervised learning algorithm for grouping similar data points together.

Description:

K-Means Clustering: This algorithm partitions data into a predefined number of clusters (k) based on feature similarity. It iteratively assigns data points to clusters and updates centroids to minimize intra-cluster variance, helping to optimize processes like inventory management and job sequencing (Sharma, 2025).

However, K-Means has **limitations** in handling **high-dimensional data** and **outliers**, and it assumes clusters are spherical, which may not always reflect real-world supply chain dynamics (Gupta et al., 2023).

4.5.3.2. DBSCAN AND GMM

Alternative clustering approaches, such as **DBSCAN (Density-Based Spatial Clustering of Applications with Noise) and Gaussian Mixture Models (GMM)**, are often needed for **non-linear and density-based clustering,** identifying clusters of arbitrary shape and handling noise in the data, which can be useful for market segmentation (J. E. Choi et al., 2022; Ester et al., 1996).

4.5.3.3. PROS:

- **Ease of Implementation:** K-Means is straightforward to implement and understand, making it accessible for various applications across different domains (ifttt-user, 2022).
- **Simplicity and Efficiency:** K-Means is straightforward to implement and understand, making it accessible for various applications. Its computational efficiency allows it to handle large datasets relatively quickly (*K-Means Pros & Cons*, n.d.; Optimove, n.d.).

- **Scalability:** The algorithm can scale well with large datasets, making it suitable for applications in supply chain management, where vast amounts of data need to be processed (*K-Means Pros & Cons*, n.d.; Optimove, n.d.).
- **Versatility:** K-Means can be applied to a wide range of data types and domains, from market segmentation to inventory management, due to its ability to group data based on feature similarity (ifttt-user, 2022; Optimove, n.d.).
- **Interpretability:** The resulting clusters and centroids are easy to interpret, providing clear insights into the structure of the data (Optimove, n.d.).

4.5.3.4. CONS:

- **Sensitivity to Initialization:** The choice of initial centroids can significantly affect the final clusters. Poor initialization can lead to suboptimal clustering results (ifttt-user, 2022).
- **Requires Predefined k:** The number of clusters (k) must be specified in advance, which can be challenging to determine without prior knowledge of the data (ifttt-user, 2022)..
- **Assumes Spherical Clusters:** K-Means assumes that clusters are spherical and of similar size, which may not always be the case in real-world data. This assumption can lead to inaccurate clustering for complex datasets (ifttt-user, 2022; Iliyas Karim et al., 2024).
- **Sensitive to Outliers:** Outliers can disproportionately affect the centroid calculations, leading to distorted clusters. This sensitivity can be a significant limitation in datasets with noise (ifttt-user, 2022; somakaushik98, n.d.).

4.5.4. OPTIMIZATION ALGORITHMS FOR RESOURCE ALLOCATION & PRODUCTION SCHEDULING

4.5.4.1. GENETIC ALGORITHMS (GA) FOR SCHEDULING EFFICIENCY

Genetic Algorithms are inspired by natural selection and are used to solve complex optimization problems.

Description:

- **Genetic Algorithms (GA):** These algorithms mimic evolution by generating and refining multiple solutions to find the most optimized one. They are particularly effective in navigating complex, multi-dimensional search spaces and balancing multiple objectives (Dennis Kallina, 2021; Mehta, 2022).

4.5.4.2. ANT COLONY OPTIMIZATION (ACO) FOR PRODUCTION FLOW OPTIMIZATION

Ant Colony Optimization is a nature-inspired algorithm used for solving complex combinatorial optimization problems.

Description:

- **ACO:** Inspired by the foraging behavior of real ant colonies, ACO uses artificial ants to find optimal paths through a problem space. It is effective in routing optimization and scheduling problems, where it dynamically adjusts production sequences based on real-time constraints (Mihai Andrei, 2024).

4.5.4.3. PARTICLE SWARM OPTIMIZATION (PSO) FOR RESOURCE ALLOCATION

Particle Swarm Optimization is a computational method inspired by the social behavior of bird flocking or fish schooling.

Description:

- **PSO:** This algorithm uses swarm intelligence to optimize resource utilization and workload balancing. It simulates collective intelligence to dynamically adjust scheduling and resource distribution, balancing machine loads, and minimizing energy consumption (Kennedy & Eberhart, 1995)**.**

4.5.4.4. PROS:

- **High Efficiency**: **GA, PSO, and ACO** are all capable of solving large-scale, complex scheduling and allocation problems quickly (Zhi Chen et al., 2025).
- **Adaptability to Real-Time Changes: ACO and PSO** dynamically adjust schedules in uncertain environments such as manufacturing disruptions and supplier delays (Zhi Chen et al., 2025).
- **Multi-Objective Optimization: GA and PSO** optimize multiple constraints simultaneously, such as minimizing costs while maximizing efficiency (Ziang Liu et al., 2024).
- **Scalability**: These algorithms work for small, medium, and large-scale SCM applications.

4.5.4.5. CONS:

- **Computational Complexity**: GA and ACO require high computational power, especially when dealing with large-scale supply chain networks (Qi Liu et al., 2022).
- **Slower Convergence in Dynamic Environments**: PSO can struggle with premature convergence and may require fine-tuning for dynamic supply chain applications (Shaqarin & Noack, 2023).
- **Parameter Sensitivity**: GA and PSO require careful selection of mutation rates, crossover probabilities, and swarm sizes, which makes implementation challenging (Mewael Isiet & M. S. Gadala, 2020).
- **Data Dependency:** ACO and PSO require high-quality historical data for optimal results, limiting their usability in low-data environments (Saptarshi Sengupta et al., 2018).

4.5.5. NATURAL LANGUAGE PROCESSING (NLP) FOR PRODUCTION INSIGHTS

4.5.5.1. SENTIMENT ANALYSIS & AI-ASSISTED SCHEDULING

Introduction: Natural Language Processing (NLP) techniques, such as sentiment analysis, are crucial for extracting insights from textual data in supply chain management.

Description:

- Sentiment **Analysis**: NLP-driven sentiment analysis extracts insights from operator reports, machine feedback logs, and supplier communications. It helps in understanding customer satisfaction levels and areas for improvement (Ideamaker, 2024).
- **BERT (Bidirectional Encoder Representations from Transformers)**: BERT is a transformer-based model that understands context and nuances in text, making it suitable for more accurate sentiment analysis and AI-assisted scheduling.

4.5.5.2. CHATBOTS FOR SUPPLIER COMMUNICATION:

- NLP-powered chatbots automate interactions with suppliers and stakeholders, streamlining communication and reducing manual workload (Ihnatchyck, 2024; Lintermans, 2022).

4.5.5.3. NAMED ENTITY RECOGNITION (NER):

- NER models classify text into categories, facilitating the organisation of unstructured data, which is essential for efficient SCM operations (Ihnatchyck, 2024).

4.5.5.4. TOPIC MODELING AND LATENT DIRICHLET ALLOCATION (LDA):

- These unsupervised learning techniques analyse large datasets to identify patterns and trends, aiding in market trend analysis and strategic decision-making (Ihnatchyck, 2024).

4.5.5.5. SEMANTIC PARSING:

- This technique transforms natural language queries into structured database queries, allowing users to interact with databases without extensive programming knowledge, thereby improving data accessibility (Ihnatchyck, 2024).

4.5.5.6. RISK IDENTIFICATION:

- NLP analyses unstructured data from sources like news articles and social media to detect potential risks and trends impacting suppliers, enhancing risk management strategies (measuredrisk, n.d.).

4.5.5.7. ERROR DETECTION IN DATASETS:

- NLP identifies inconsistencies and errors in datasets, ensuring data quality and reliability in supply chain operations (Ihnatchyck, 2024).

4.5.5.8. PROS:

- **Enhanced Decision-Making:** NLP converts unstructured data into structured insights, supporting informed decision-making across SCM and PP functions (Ihnatchyck, 2024).
- **Improved Efficiency**: Automating data analysis tasks with NLP reduces manual effort, leading to faster and more accurate outcomes (Lintermans, 2022; Nikhil Koranne, 2024).
- **Risk Mitigation:** Early detection of potential issues through NLP (financial reports, social media, and global events …) allows for proactive measures, minimizing disruptions in the supply chain (measuredrisk, n.d.).

4.5.5.9. CONS:

- **Data Privacy Concerns:**
  - Processing sensitive information with NLP raises privacy issues, necessitating robust data protection measures (Rotenberg, 2024).
  - The use of NLP-powered **Chatbots and Risk Identification Models** raises data privacy risks, as they process large volumes of confidential supplier and financial data (Rotenberg, 2024).

- **Integration Challenges:** Incorporating NLP into existing systems can be complex and may require significant adjustments to workflows (Ihnatchyck, 2024; packagex, 2023).
- **Dependence on Data Quality: Error Detection NLP models** require high-quality input data, and any inconsistencies or biases in historical data can lead to incorrect supply chain predictions (Ihnatchyck, 2024).
- **Resource Intensive: Topic Modeling (LDA) and Advanced NLP-Based Predictive Analytics** demand significant computational resources and skilled personnel for successful implementation, impacting the overall return on investment (Ihnatchyck, 2024).

4.5.6. EXPLAINABILITY AND INTERPRETABILITY FOR ENHANCED DECISION-MAKING

The integration of **Artificial Intelligence (AI), the Internet of Things (IoT), and human-machine interfaces** connects hardware and software systems to optimize automation processes in **Supply Chain Management (SCM)**. As industries transition towards **Industry 5.0**, the focus shifts from machine-centred operations to **human-centred AI**, where AI technologies augment human decision-making to enhance productivity. In this context, **Explainable AI (XAI)** and **Interpretable Machine Learning (iML)** are crucial for **ensuring transparency in SCM decision-making**, allowing stakeholders to understand, trust, and effectively act upon AI-generated insights.

AI-driven SCM systems rely on **real-time data processing, predictive analytics, and automation** to enhance operational efficiency. However, without proper explainability, AI's decision-making processes remain opaque, hindering user trust and adoption. The distinction between **explainability and interpretability** in AI is often debated. Some researchers consider them interchangeable, while others argue that **explainability focuses on understanding model outputs (e.g., SHAP, LIME)** and **interpretability pertains to the model's intrinsic transparency (e.g., decision trees, logistic regression)**.

The study (El Oualidi & Assar, 2024) provides a structured exploration of **XAI, iML, and their impact on SCM processes**, making AI-driven insights more actionable across different levels of supply chain management.

4.5.6.1. KEY CONCEPTS: EXPLAINABILITY, INTERPRETABILITY, AND AI IN SCM

4.5.6.1.1. EXPLAINABLE ARTIFICIAL INTELLIGENCE (XAI)

XAI improves trust and adoption of AI-based **supply chain decision-support systems** by making AI outputs comprehensible. **Key XAI methods include**:

- **Model-Agnostic Methods** (e.g., SHAP, LIME) – Explain various AI models, including deep learning.
- **Model-Specific Methods** (e.g., Class Activation Mapping for CNNs) – Tailored to specific architectures.
- **Local vs. Global Explanations** – **Local explanations** focus on individual AI decisions, while **global explanations** provide an overall model view.

4.5.6.1.2. INTERPRETABLE MACHINE LEARNING (IML)

iML ensures that **SCM decision models are inherently transparent**, allowing users to **trace and understand** AI-generated predictions. Unlike XAI (which provides post-hoc explanations), **iML prioritizes models that are interpretable by design**, such as:

- **Decision Trees**

- **Generalized Additive Models (GAMs)**
- **Explainable Boosting Machines (EBMs)**

By integrating **iML techniques into AI-driven SCM systems**, organisations enhance **real-time decision-making, risk assessment, and operational efficiency**.

4.5.6.2. AI-POWERED SCM APPLICATIONS AND EXPLAINABILITY CHALLENGES

SCM processes require real-time AI-driven decision-making across various domains:

- **Demand Forecasting:** AI predicts future demand fluctuations based on historical sales data.
- **Inventory Optimization:** AI balances stock levels to reduce shortages or excess inventory.
- **Supply Chain Risk Management:** AI assesses supply chain disruptions using external data (weather, market conditions, geopolitical risks).
- **Route Optimization:** AI-driven logistics optimize transportation and distribution networks.
- **Supplier Selection & Procurement:** AI evaluates suppliers based on cost, reliability, and sustainability.

However, these AI applications raise challenges related to **explainability**:

- **How does an AI model determine inventory reorder points?**
- **Why does AI recommend a specific supplier over another?**
- **What factors influence AI-driven logistics route selection?**

Ensuring **SCM stakeholders understand AI-driven decisions** is vital for building **trust, compliance, and operational efficiency**.

4.5.6.3. MODEL-SPECIFIC EXPLAINABILITY METHODS IN SCM

AI models applied in SCM require **explainability techniques** tailored to **specific supply chain functions**. The following methods enhance model transparency in **forecasting, optimization, and logistics**:

4.5.6.3.1. CLASS ACTIVATION MAPPING (CAM) & GRADCAM

- Applied in **visual AI systems for warehouse automation**.
- Highlights **critical features in machine vision models**, enabling logistics managers to interpret **image-based AI predictions**.

4.5.6.3.2. DIFFI (DEPTH-BASED ISOLATION FOREST FEATURE IMPORTANCE)

- Used in **anomaly detection for inventory optimization**.
- Helps identify **supply chain disruptions by explaining outliers in stock movement patterns**.

4.5.6.3.3. LIONFORESTS

- Enhances **supply chain risk analysis**.
- Generates **IF-THEN decision rules**, making AI predictions more interpretable.

4.5.6.3.4. SALIENCY MAPS

- Applied in **AI-based logistics route optimization**.
- Highlights **key geographic and operational constraints influencing AI-generated transportation routes**.

4.5.6.3.5. ARCANA (AUTOENCODER-BASED ANOMALY ROOT CAUSE ANALYSIS)

- Used in **supply chain failure analysis**.
- Identifies **critical weak points in supplier networks and logistics hubs**.

These methods enhance **interpretability, allowing supply chain professionals to trust and act on AI-driven insights**.

4.5.6.4. COMBINING EXPLAINABILITY METHODS FOR SCM OPTIMIZATION

Recent research suggests that **multiple explainability methods should be combined** to ensure **SCM decision-makers receive holistic AI insights**:

- **Stacked Approach:**
  - Methods are applied sequentially to **generate AI-driven supply chain insights**.
  - Example: **SHAP combined with XGBoost for supplier risk assessment**.
- **Simultaneous Approach:**
  - Multiple methods provide **different perspectives on AI-generated decisions**.
  - Example: **LIME + SHAP for AI-based demand forecasting**.
- **Method Comparison:**
  - Evaluates **explainability methods for consistency and reliability**.
  - Example: **Ferraro et al. compared SHAP and LIME for AI-based supply chain optimization**.
- **AutoML Integration:**
  - Combines **AutoML with explainability tools** for **automated supply chain decision-making**.
  - Example: **LIME + SHAP within AutoML for AI-driven procurement optimization**.

By integrating **these methods, SCM professionals can improve AI transparency and ensure informed, data-driven decision-making**.

4.5.6.5. CHALLENGES AND FUTURE DIRECTIONS IN EXPLAINABLE AI FOR SCM

Despite advances in XAI and iML, **several challenges remain in AI-driven SCM applications**:

4.5.6.5.1. PURPOSE OF EXPLANATIONS

Different SCM stakeholders require **varying levels of AI transparency**:

- **Supply Chain Managers** need actionable insights with minimal complexity.
- **Data Scientists** require detailed model diagnostics for performance optimization.

4.5.6.5.2. STANDARDIZATION OF EXPLANATION METRICS

Unlike traditional **SCM performance metrics (cost, lead time, efficiency)**, AI explanations lack **industry-wide standards**.

4.5.6.5.3. HUMAN-AI COLLABORATION IN SCM

- AI models should be designed to **augment human decision-making**.
- **Human-in-the-loop AI approaches** ensure AI models remain adaptable to **real-world SCM complexities**.

4.5.6.5.4. AI EXPLAINABILITY IN GREEN SUPPLY CHAINS

As sustainability becomes a priority, **explainable AI can enhance environmental impact assessments**, enabling organisations to:

- **Optimize carbon footprints in logistics.**
- **Reduce energy consumption through AI-driven supply chain optimization.**

4.5.6.6. CONCLUSION

The rise of AI in SCM demands a balance between automation and human oversight. Explainable AI (XAI) and Interpretable Machine Learning (iML) are essential for building trust in AI-driven supply chain systems.

Future research should focus on:

- Standardizing AI explainability metrics in SCM.
- Developing audience-specific AI explanations for supply chain stakeholders.
- Enhancing human-AI collaboration for more adaptive and resilient supply chains.

By addressing these challenges, AI-driven SCM systems can achieve higher transparency, efficiency, and trust, paving the way for more sustainable and human-centric supply chains.

5. LEVERAGING EMERGING DIGITAL TECHNOLOGIES FOR SCM 4.0

The following chapter details how **AI-driven solutions** can significantly enhance Supply Chain Management (SCM) across **strategic and operational levels (PP, S&OP, MPS, MRP and I/FCS)**, outlining their **roles, benefits, limitations, and key references.**

5.1. AI-DRIVEN PROFIT PLANNING IN SCM

Emerging **Industry 4.0** technologies - such as **Artificial Intelligence (AI), Big Data, IoT, Blockchain, and Cloud Computing** - have transformed **profit planning** by improving forecasting accuracy, automating financial processes, and optimizing resource allocation.

Here's how these technologies can contribute.

5.1.1. ENHANCED DATA COLLECTION AND ANALYSIS

Data-driven decision-making is central to modern profit planning, with AI technologies improving the **quality, speed, and depth of financial analysis**.

- **Machine Learning (ML):**
  - ML models predict **revenue trends, cost fluctuations, and profitability drivers**, enabling proactive financial planning (Sam Phipps, 2025).
  - ML-based assessments help quantify the **financial impact and risks** of different business strategies (Colback, 2024).
- **Deep Learning & Neural Networks:**
  - AI-based **profit simulations** help organisations **assess different financial scenarios** and their long-term impact (Colback, 2024).
- **IoT for Real-Time Data Capture:**
  - IoT devices **track operational efficiency**, providing live updates on **inventory, production costs, and supply chain disruptions** to optimise financial performance.

5.1.2. IMPROVED DECISION-MAKING

AI enables **predictive and prescriptive analytics**, allowing businesses to make **data-driven, forward-looking decisions** in profit planning.

- **Predictive Analytics:**
  - AI models anticipate **market trends, consumer behavior, and economic fluctuations**, allowing businesses to adjust pricing, inventory, and operational costs dynamically (Colback, 2024).
- **Scenario Simulation & Risk Forecasting:**

- AI-powered simulations **analyse different financial strategies** under various economic conditions, enhancing risk management and strategic decision-making.

- **NLP for Cost Analysis & Forecasting:**
  - NLP algorithms process **historical financial reports, market news, and supplier contracts** to predict future **cost trends, improving budgeting accuracy** (Ihnatchyck, 2024).
  - NLP-driven **topic modeling (LDA)** identifies cost patterns across **supplier contracts, financial statements, and industry reports**, aiding in cost forecasting ((Krishnan & Majumdar, 2021).

- **Market Sentiment Analysis:**
  - AI-powered **NER (Named Entity Recognition)** extracts insights from **financial reports, news, and customer reviews**, improving investment and pricing decisions (Bridget Rice, 2024).

5.1.3. OPERATIONAL EFFICIENCY IN PROFIT PLANNING

AI enhances **cost efficiency, supply chain resilience, and process automation**, leading to improved profitability.

- **Automation of Routine Financial Tasks:**
  - AI-powered **Robotic Process Automation (RPA)** reduces manual errors, **automates invoicing, financial reporting, and risk analysis**, and **lowers operational costs.**

- **Supply Chain Optimization:**
  - **IoT-enabled tracking systems** monitor real-time shipments, **reducing delays and excess inventory costs**.
  - **AI-based supplier segmentation** optimizes procurement by grouping suppliers based on **lead time, cost variability, and quality ratings** (Fran Quilty, 2022).

- **Optimization Algorithms in Resource Allocation:**
  - **Genetic Algorithms (GA):** Identify the **most profitable product mixes and pricing strategies** by simulating multiple financial scenarios (Faizatulhaida Md Isa et al., 2023).
  - **Particle Swarm Optimization (PSO):** AI-driven **resource allocation models** optimize **financial and operational spending** to maximize profitability (Sahar Khajesaeedia et al., 2025).

5.1.4. ENHANCED CUSTOMER INSIGHTS & PROFITABILITY

AI-driven analytics refine **pricing strategies, customer segmentation, and revenue optimization**.

- **Clustering for Product & Customer Segmentation** (Mahya Seyedan & Fereshteh Mafakheri, 2020):
  - K-Means categorizes **product lines based on profitability**, enabling targeted promotions.
  - **Customer segmentation** refines **pricing strategies**, increasing conversion rates (Ivanov et al., 2017).

- **Data Analytics for Customer Insights:**
  - AI-driven **customer behaviour analysis** helps refine personalized **marketing strategies**, increasing **repeat purchases and brand loyalty**.

- **NLP for Market Sentiment Analysis** (Bridget Rice, 2024):
  - AI extracts insights from **financial reports, news, and customer feedback**, fine-tuning sales forecasts and promotions.

- **Clustering Algorithms for Profitability Segmentation:**
  - **Machine Learning for Dynamic Pricing** (Jang, 2025): AI-based pricing models **adjust product prices** in response to **demand, competition, seasonality and consumer sentiment** (Adam Hayes, 2025).
  - AI clusters **high-margin vs. low-margin products**, enabling businesses to refine **pricing models and promotions** (C. Chen et al., 2023).
  - Supplier segmentation helps optimize **cost negotiations** and **profit margins** by grouping suppliers based on price trends, lead time, and service quality.

5.1.5. FINANCIAL INNOVATION & AI-DRIVEN INVESTMENTS

AI and digital technologies are **reshaping financial planning, investment strategies, and risk management** in supply chains.

- **Digital Payment Systems & Blockchain:**
  - Blockchain-based **smart contracts** automate **financial transactions, reduce fraud, and streamline cash flow management** (Adam Hayes, 2025).

- **Algorithmic Trading & AI-Driven Investment Strategies:**
  - AI enhances **automated trading strategies**, optimizing investment portfolios and **maximizing returns**.

- **Risk Identification through NLP & AI:**
  - NLP models scan **supplier contracts, financial statements, and global trade policies**, detecting **financial risks before they escalate** (measuredrisk, n.d.).
  - AI processes **economic news, market data, and government reports** to forecast potential **financial disruptions** (Krishnan & Majumdar, 2021).

5.1.6. AI-DRIVEN PROFIT PLANNING TOOLS & AI ADOPTION IN EUROPE

Among the **210 profit planning tools** analysed (gartner, 2024), the most recognized solutions in **Europe** include:

- **Anaplan** (Anaplan, n.d.)
  - An AI-powered **financial planning platform** for **forecasting, budgeting, and scenario analysis**.

- **Workday Adaptive Planning**
  - An enterprise **financial modeling and cost optimization tool**, widely used in **corporate finance and supply chain management** (Prophix, 2024).

5.1.7. CONCLUSION

The integration of **AI, ML, IoT, and digital finance technologies** has **redefined profit planning**, enabling businesses to **enhance decision-making, optimize financial performance, and anticipate market risks**.

- **Predictive analytics, clustering, and optimization algorithms** enhance **profitability and risk mitigation**.
- **Automation and digital finance innovations** streamline **cost management and resource allocation**.
- **AI-driven customer insights and dynamic pricing** increase **profit margins and market adaptability**.

Future advancements in **Explainable AI (XAI), automated financial modeling, and blockchain-based financial planning** will further **improve transparency, scalability, and resilience** in AI-powered **profit planning strategies**.

5.2. AI-DRIVEN S&OP IN SCM

Artificial Intelligence (AI) has significantly transformed **Sales and Operations Planning (S&OP)** by improving **forecasting accuracy, inventory optimization, and decision-making processes**. Through **Machine Learning (ML), Deep Learning, Clustering, Optimization Algorithms, and Natural Language Processing (NLP)**, AI enhances **demand forecasting, resource allocation, and real-time supply chain adjustments**.

This chapter explores key AI-driven methodologies applied in S&OP, their benefits, and real-world applications.

5.2.1. DEMAND FORECASTING & PLANNING

AI-driven **demand forecasting** enhances **accuracy, adaptability, and responsiveness**, allowing businesses to anticipate market trends and optimize inventory levels.

- **Machine Learning (ML) for Demand Forecasting** (Jang, 2025; Random Forests, 2023; Sruthi, 2021):
    - **AI** and **machine learning** are increasingly used in S&OP to improve forecasting accuracy and streamline decision-making. (Vinay Rajani, Preeti AryaCrossman, 2023)
    - **Decision Trees & Random Forests** detect **relationships between sales trends, seasonality, and economic indicators**, improving forecast precision (Banoth, 2024).
    - **Support Vector Machines (SVMs)** classify demand patterns, identifying fluctuations and demand shifts (Jang, 2025).
    - **Gradient Boosting Machines (GBM) & XGBoost** improve forecast accuracy for large datasets, outperforming traditional statistical methods (T. Chen & Guestrin, 2016).
- **Neural Networks for Time-Series Forecasting** (Gołąbek et al., 2020):
    - **LSTMs** model long-term dependencies in demand, handling seasonality and macroeconomic trends.
    - **Transformer Models** (e.g., **BERT, T5**) outperform LSTMs in **multi-variable forecasting**, improving adaptability to external disruptions (Vaswani et al., 2023).
    - LLMs can assist non-technical users by generating forecasting code or helping interpret existing models. Current mainstream models are limited, but fine-tuned, purpose-built LLMs could become effective copilots for demand planners (Vinay Rajani & Preeti AryaCrossman, 2023).
        - LLMs can convert **unstructured text** (e.g., product reviews) into usable **numerical or categorical data**.
        - This structured output can be integrated into forecasting models—though **real-world, scaled adoption is still rare** at this stage.
        - LLMs can **summarize and organize structured and unstructured data**, supporting activities like:
            - Recapping assumptions from past planning meetings
            - Highlighting forecast changes
            - Tracking project statuses (e.g., product launches
- **Natural Language Processing (NLP) for Demand Signals** (Filipsson, 2024; Ihnatchyck, 2024):
    - AI extracts **customer reviews, sales conversations, and market chatter** to refine forecasts.

- Sentiment Analysis gauges consumer confidence and industry trends, adjusting forecasts accordingly.

5.2.2. MEETING SUMMARIZATION & DECISION SUPPORT

AI-powered **automation in S&OP meetings** ensures **alignment, accountability, and strategic execution**.

- **NLP for Meeting Summarization** (Ihnatchyck, 2024).
  - AI extracts key insights from **S&OP discussions, emails, and stakeholder communications**.
  - **Decision Tracking AI** assigns action items, preventing misalignment in execution.
- **Real-Time S&OP Dashboards** (AIMMS, n.d.):
  - AI-powered dashboards **visualize forecasts, sales performance, and operational risks**.

5.2.3. AI-DRIVEN TOOLS IN S&OP

The following AI-driven tools examples enhance **decision-making, automation, and efficiency** in key operational areas:

- **AIMMS:** AIMMS provides a prescriptive analytics platform that allows for modeling and optimization in various industries, enhancing decision-making processes in supply chain management (AIMMS, n.d.).
- **Alta:** Alta, an AI startup, has developed AI agents that automate sales tasks, including prospecting, research, outreach, and meeting scheduling, integrating with over 50 business tools (Webb, 2025)

5.2.4. INDUSTRY APPLICATIONS OF AI-DRIVEN TOOLS IN S&OP

AI-powered S&OP is **reshaping global supply chains**, with **real-world implementations** in multiple industries:

- **Foxconn's FoxBrain:** Foxconn has developed its own AI model, FoxBrain, designed to enhance manufacturing and supply chain management through data analysis and reasoning capabilities (Reuters, 2025; Yang Jie, 2025).
- **Amarra:** Amarra, a distributor of special-occasion gowns, utilizes AI for inventory management, resulting in a 40% reduction in overstocking (Satta Sarmah Hightower, 2025).

5.2.5. CONCLUSION

AI-driven **Sales and Operations Planning (S&OP)** has **transformed supply chain agility, accuracy, and efficiency**.

Key Takeaways:

- **Machine Learning & Deep Learning** improve **demand forecasting and sales planning**.
- **Hybrid AI models** combine **multiple methodologies for higher accuracy, adaptability, and decision support**.

Future Trends:

- **Explainable AI (XAI) for real-time S&OP insights.**
- **AI-driven autonomous decision-making in supply chain networks.**
- **Integration of AI-powered digital twins for predictive simulations.**

By embracing **AI-driven S&OP strategies**, businesses **enhance responsiveness, reduce costs, and gain competitive advantages in global markets**.

5.3. AI-DRIVEN MPS IN SCM

Master Production Scheduling (MPS) plays a **pivotal role** in supply chain management by converting **demand forecasts into detailed production plans**. Traditionally, **MPS faced challenges such as demand uncertainty, inefficient resource allocation, and scheduling rigidity**.

AI-driven technologies now **enhance MPS accuracy, adaptability, and efficiency** by leveraging machine learning, optimization algorithms, real-time data processing, and predictive analytics. These technologies allow manufacturers to **optimize scheduling, minimize downtime, allocate resources effectively, and improve decision-making**.

Below are the **key AI-driven capabilities transforming MPS**:

5.3.1. DEMAND-DRIVEN PRODUCTION PLANNING

AI-driven **production planning** aligns manufacturing schedules with **forecasted demand, minimizing inefficiencies and reducing lead times**.

- **AI Dashboards for Scheduling Optimization** (AIMMS, n.d.):
  - Provides **real-time scheduling updates, detecting bottlenecks and inefficiencies**.
  - AI **automates schedule refinement**, ensuring **minimal human intervention.**
- **Machine Learning for Predicting Scheduling Bottlenecks** (Gołąbek et al., 2020):
  - AI predicts **machine failures, capacity overloads, and resource shortages**, allowing proactive schedule adjustments.
- **Neural Networks for Machine Availability Forecasting** (Vaswani et al., 2023):
  - **LSTM networks** predict machine availability based on **historical usage patterns and real-time sensor data**, reducing idle time.

5.3.2. SUPPLIER COORDINATION & MATERIAL AVAILABILITY

AI-driven **supplier communication and material tracking** ensure a **steady flow of raw materials**.

- **NLP for Supplier Communication & Issue Detection** (Lintermans, 2022):
  - AI-powered **chatbots automate supplier inquiries, track shipments, and resolve disputes** faster.
  - **Sentiment analysis** detects potential supplier delays by analysing **emails, contracts, and financial reports** (Ihnatchyck, 2024).
- **Predictive Analytics for Material Shortages** (Filipsson, 2024):
  - AI predicts **supply chain disruptions**, adjusting **procurement schedules dynamically**.

5.3.3. DECISION TRACKING & CONTINUOUS IMPROVEMENT

AI-powered **decision intelligence** ensures **S&OP alignment, tracking, and execution accuracy**.

- **NLP for Automated Meeting Summarization** (Ihnatchyck, 2024):

    - AI extracts **key decisions from planning meetings**, ensuring **follow-ups and accountability**.
    - **Semantic Parsing converts discussions into structured action points**, aligning **production and operations teams**.

- **Real-Time AI Dashboards for Performance Monitoring** (AIMMS, n.d.):
    - AI-powered dashboards provide **real-time scheduling visibility**, detecting **delays and inefficiencies**.
    - **Continuous learning models** refine **production strategies** based on **historical data and real-time analytics**.

5.3.4. AI-DRIVEN TOOLS IN MPS

MPS requires AI-powered solutions that **translate demand forecasts into actionable production schedules**, ensuring **efficient resource allocation, batch sequencing, and production flow optimization**. We can mention the tool already selected for S&OP:

- **AIMMS Prescriptive Analytics for MPS** (AMMS, n.d.): AI-powered **master production scheduling platform**, optimizing **inventory and manufacturing timelines**.

5.3.5. INDUSTRY APPLICATIONS OF AI-DRIVEN TOOLS IN MPS

AI-driven **MPS solutions** are being widely implemented across industries to **improve scheduling efficiency and operational agility**.

- **Foxconn's FoxBrain** (Reuters, 2025; Yang Jie, 2025): AI-driven **manufacturing optimization model**, dynamically adjusting **production schedules**.
- **Amarra AI for Inventory & Scheduling** (Satta Sarmah Hightower, 2025): AI-based **order clustering and batch scheduling**, reducing **overstock by 40%**.

5.3.6. CONCLUSION

AI-driven **Master Production Scheduling (MPS)** ensures **real-time adaptability, efficiency, and optimized resource utilization**, revolutionizing manufacturing workflows.

Key Takeaways:

- **Machine Learning & Neural Networks** predict **scheduling bottlenecks and optimize machine availability**.
- **NLP for Supplier Communication & Issue Detection**
- **Predictive Analytics for Material Shortages**
- **Hybrid AI models** improve **multi-objective scheduling, balancing efficiency and cost**.

Future Trends:

- **AI-powered Digital Twins for MPS simulations**.
- **Self-learning scheduling models using reinforcement learning**.
- **Fully autonomous AI-driven production control systems**.

By integrating AI into **MPS workflows**, businesses **enhance production agility, reduce operational costs, and maintain resilience in volatile markets**.

5.4. AI-DRIVEN MRP IN SCM

Material Requirements Planning (MRP) is a **key function in supply chain management**, ensuring that raw materials, components, and parts are available **at the right time, in the right quantity, and at the lowest cost**. Traditionally, MRP systems **struggled with demand fluctuations, inventory imbalances, and supply chain disruptions**, often relying on static forecasts that failed to adapt to real-world variability.

With the integration of **AI-driven technologies**, MRP has evolved into a **dynamic and adaptive system** capable of **real-time decision-making**. AI enables **faster reaction times** by continuously processing **real-time demand signals, supplier updates, and production constraints**, ensuring that procurement and inventory adjustments are made proactively.

This results in:

- **Better demand forecasting**, reducing material shortages and excess inventory.
- **Automated supply chain adjustments**, responding dynamically to disruptions.
- **Improved procurement efficiency**, minimizing delays and supplier risks.
- Real-time optimization of material flow, ensuring production continuity.

Below are the key AI-driven capabilities transforming MRP

5.4.1. DEMAND-DRIVEN MATERIAL PLANNING

AI enhances **MRP responsiveness** by dynamically aligning **procurement and inventory strategies** with **real-time production and demand fluctuations**.

- **Machine Learning for Demand Forecasting & Inventory Control** (Banoth, 2024; Pedro R., 2024):
  - AI predicts **material shortages and overstock risks**, preventing supply chain disruptions.
  - **Decision Trees & Random Forests** analyse historical inventory usage, supplier lead times, and seasonal demand trends.
- **Deep Learning for Procurement Accuracy** (Pedro R., 2024):
  - **LSTM networks & Transformers** forecast **real-time supply chain needs**, improving procurement accuracy.
  - **Adaptive AI models** dynamically adjust **raw material orders** based on production trends.
- **Clustering for Material Prioritization** (Danaka M. Porter, 2018):
  - AI groups raw materials based on **demand variability, supplier reliability, and production urgency**.
  - **Ensures critical materials receive priority** while optimizing inventory turnover.

5.4.2. SUPPLIER SELECTION & PROCUREMENT OPTIMIZATION

AI enhances **supplier evaluation, contract negotiation, and procurement efficiency**, minimizing risks and delays.

- **Machine Learning for Supplier Evaluation** (Banoth, 2024; Jang, 2025):
  - AI **classifies suppliers** based on cost, reliability, and lead times, automating selection processes.
  - **Support Vector Machines (SVMs)** identify **high-risk suppliers**, improving procurement decisions.

- **K-Means Clustering for Procurement Strategy Optimization** (Danaka M. Porter, 2018):
  - AI segments **suppliers into strategic groups**, optimizing procurement schedules.
  - Ensures a **diversified supplier base**, reducing dependency risks.
- **Optimization Algorithms for Multi-Tiered Supplier Coordination** (Chauhan et al., 2023; Kallina, 2021):
  - **Genetic Algorithms (GA)** adjust **material orders dynamically**, ensuring procurement aligns with real-time production needs.
  - **PSO & ACO optimize supplier selection and material flow**, minimizing waste and procurement inefficiencies (Boute & Udenio, 2021).

5.4.3. INVENTORY MANAGEMENT & REPLENISHMENT

AI-driven **inventory optimization** reduces **holding costs, prevents shortages, and ensures seamless production flow**.

- **Clustering for Inventory Optimization** (Danaka M. Porter, 2018):
  - **AI groups parts based on demand cycles**, ensuring efficient material stocking.
  - Helps prevent **supply chain disruptions** by prioritizing essential materials.
- **NLP for Automated Inventory Optimization** (Filipsson, 2024):
  - AI evaluates **supplier catalogs and delivery schedules**, optimizing **inventory levels**.
  - **Chatbots automate replenishment requests**, ensuring real-time stock updates (Ihnatchyck, 2024).
- **PSO for Dynamic Stock Balancing** (Kennedy & Eberhart, 1995):
  - AI dynamically adjusts **stock levels across warehouses**, reducing over-ordering.

5.4.4. LOGISTICS & MATERIAL FLOW OPTIMIZATION

AI-driven logistics solutions **ensure efficient material transport and minimize supply chain disruptions**.

- **Ant Colony Optimization (ACO) for Logistics Routing** (Mihai Andrei, 2024):
  - AI **optimizes material delivery routes**, reducing transit times and supplier bottlenecks.
  - **Dynamically reroutes shipments** based on delays, weather conditions, or warehouse constraints.
- **Genetic Algorithms for Warehouse Allocation** (Chauhan et al., 2023):
  - AI balances **warehouse space utilization**, preventing overstocking while ensuring supply continuity.
- **Real-Time AI for Procurement Adjustments** (PlanetTogether, 2024; Rootstock Software, 2024):
  - AI processes real-time supplier performance data, allowing procurement teams to adj**ust purchase orders instantly**.

5.4.5. SUPPLIER RELATIONSHIP MANAGEMENT & RISK MITIGATION

AI enhances **supplier monitoring, risk assessment, and compliance tracking**.

- **NLP for Supplier Communication Analysis** (Ihnatchyck, 2024; Lintermans, 2022):
  - AI-powered chatbots automate **supplier interactions, inquiries, and dispute resolution**.
- **Sentiment Analysis for Supplier Evaluation** (Ideamaker, 2024):

- AI extracts insights from **contracts, pricing trends, and vendor reviews**, refining supplier selections.

- **Risk Identification in Supplier Relations** (measuredrisk, n.d.):
  - AI analyses **supplier history, compliance records, and performance reviews**, flagging high-risk vendors.

5.4.6. DECISION INTELLIGENCE FOR MRP

AI-powered **decision-support systems** refine **MRP strategies and procurement planning**.

- **AI Dashboards for MRP Decision Support** (AIMMS, n.d.):
  - Provides **real-time insights on inventory levels, procurement risks, and supply chain disruptions**.
- **NLP for Meeting Summarization & Action Tracking** (Ihnatchyck, 2024):
  - AI **converts procurement discussions into structured actions**, ensuring alignment between MRP and production teams.

5.4.7. AI-DRIVEN TOOLS IN MRP

MRP relies on AI-powered solutions that **ensure raw materials and components are available at the right time and in the right quantities**. The selected tools improve **supplier management, demand forecasting, and procurement efficiency**, ensuring **optimal inventory levels while preventing shortages or excess stock**.

Here are two examples of Material Requirements Planning (MRP) tools that integrate AI-driven solutions and support multi-level Bills of Materials (BOM):

- **Streamline:** it is an AI-powered platform that offers advanced demand forecasting, inventory optimization, and material requirements planning. It integrates demand forecasts with multi-level BOMs to generate precise production schedules and material requirements. (Streamline, n.d.)
- **ketteQ**: this Supply Planning solution leverages AI-driven, real-time adaptability to enhance manufacturing and distribution operations. It supports multi-level BOMs, constraint-based replenishment planning, and dynamic scenario analysis, enabling proactive adjustments to changing conditions and optimization of supply chain performance (Ketteq, n.d.).

These tools are recognized for their ability to enhance material planning and production processes, catering to businesses with varying needs and sizes.

5.4.8. INDUSTRY APPLICATIONS OF AI-DRIVEN TOOLS IN MRP

Industries are **leveraging AI for MRP improvements**, focusing on **real-time procurement, inventory balance, and supplier optimization**.

- **BMW's AI-Driven Supplier Coordination** (BMWGroup, n.d.)
  - **BMW** utilizes its **Connected Supply Chain (CSC) system** to enhance supplier coordination. This system updates material controllers and logistics specialists on the location of goods in the supply chain and estimated delivery times every 15 minutes. The CSC system lays the foundation for predictive analytics and artificial intelligence (AI) in supply chain control.
- **Siemens' Digital Twin for Real-Time MRP** (Siemens, n.d.-a)
  - **Siemens** offers a comprehensive **Digital Twin solution** that integrates **real-time** data, simulation, and modeling techniques to mirror the behavior, characteristics, and performance of physical counterparts. This technology enables manufacturers to

design, simulate, and optimise products, machines, production, and entire plants in the digital world before implementing changes in the real world.

- **BASF AI-Powered Chemical Raw Material Planning** (BASF, n.d.)
  - AI **optimizes chemical inventory levels**, reducing waste and improving material efficiency.

5.4.9. CONCLUSION

AI-driven **Material Requirements Planning (MRP)** ensures **real-time adaptability, efficiency, and risk mitigation**, revolutionizing supply chain material flow.

Key Takeaways:

- **Machine Learning & Deep Learning** enhance **demand forecasting and supplier evaluation**.
- **Clustering & Optimization Algorithms** improve **inventory segmentation, procurement strategy, and logistics routing**.
- **NLP-driven automation** refines **supplier communication, risk assessment, and contract negotiation**.
- **ACO & PSO models** optimize **material flow, reducing supply chain disruptions**.
- **Hybrid AI models** improve **MRP decision-making, balancing cost, efficiency, and risk management**.

Future Trends:

- **AI-powered Autonomous Procurement Systems** for self-adjusting material orders.
- **Integration of Digital Twins for MRP scenario simulations**.
- **Explainable AI (XAI) in procurement decision intelligence**.

By integrating **AI into MRP workflows**, businesses **enhance material planning agility, reduce operational costs, and maintain resilience in volatile markets**.

5.5. AI-DRIVEN FCS & ICS IN SCM

Finite Capacity Scheduling (FCS) and Infinite Capacity Scheduling (ICS) are critical components of **production planning and resource allocation** within supply chain management. **FCS** considers **resource limitations** such as machine availability, workforce constraints, and production bottlenecks, ensuring that schedules are feasible based on real-world constraints. In contrast, **ICS** assumes **unlimited capacity**, generating theoretical schedules that require manual adjustments to accommodate actual production limitations.

Historically, both FCS and ICS systems **struggled with inefficiencies, unpredictable demand shifts, and resource bottlenecks** due to **rigid planning methods and static forecasting models**. However, the integration of **AI-driven technologies** has transformed FCS and ICS into **dynamic, real-time responsive systems**, enabling manufacturers to:

- Predict bottlenecks and optimize resource allocation, ensuring balanced workloads.
- Adapt schedules dynamically, responding instantly to machine failures, labor shortages, or supply chain disruptions.
- Enhance decision-making with real-time insights, reducing manual interventions.
- Improve overall production efficiency, minimizing downtime and maximizing throughput.

With AI-powered real-time processing, FCS now becomes more adaptive, enabling automated schedule adjustments based on real-time shop-floor conditions. Likewise, ICS becomes more practical, as AI refines theoretical schedules to align with actual capacity constraints.

Below are the key AI-driven capabilities transforming FCS and ICS:

5.5.1. DYNAMIC JOB SCHEDULING & CAPACITY PLANNING

AI-powered scheduling enhances **resource allocation, workload balancing, and production sequencing** in **Finite Capacity Scheduling (FCS)** and **Infinite Capacity Scheduling (ICS)**.

- **Machine Learning for Dynamic Scheduling Adjustments** (Deskera, 2023; Rootstock Software, 2024):
  - AI **adapts schedules dynamically** based on **real-time production constraints**.
  - **Decision Trees & Random Forests** identify the **most efficient sequencing of production tasks**, optimizing workflow **by predicting bottlenecks** (Mehta, 2022).
- **Deep Learning for Shift Planning & Workforce Optimization** (Mehta, 2022):
  - **LSTM models** forecast **machine availability and workforce productivity**, reducing scheduling conflicts.
  - **Transformer-based AI models (BERT, GPT)** analyse workforce reports and production logs, detecting potential inefficiencies.
- **Optimization of Job Sequencing via AI** (Mehta, 2022):
  - AI determines **optimal job order**, **reducing machine transition times and resource idling**.
  - **Support Vector Machines (SVMs)** classify tasks based on **priority, resource availability, and lead times**, automating **real-time scheduling decisions** (Jang, 2025).

5.5.2. RESOURCE ALLOCATION & PRODUCTION FLOW OPTIMIZATION

AI dynamically optimizes **machine workloads, workforce distribution, and production throughput**.

- **Particle Swarm Optimization (PSO) for Capacity Planning** (Kennedy & Eberhart, 1995):
  - AI **allocates production capacity efficiently**, balancing workloads to prevent **bottlenecks**.
  - PSO reduces **idle time and machine downtime**, improving **operational efficiency**.
- **Genetic Algorithms (GA) for Multi-Objective Scheduling** (Dennis Kallina, 2021; Mehta, 2022):
  - AI **evolves multiple scheduling scenarios**, selecting the **most optimal resource distribution**.
  - GA balances **machine loads, workforce availability, and shift timing dynamically**.
- **Ant Colony Optimization (ACO) for Production Flow** (Mihai Andrei, 2024):
  - AI-based scheduling **dynamically adjusts production sequences** based on **real-time shop-floor conditions**.
  - **ACO-enhanced routing** ensures **seamless job sequencing**, **reducing setup times and lead times**.

5.5.3. JOB SEQUENCING & WAREHOUSE CLUSTERING

AI-driven **clustering models** improve **task scheduling, inventory classification, and warehouse storage allocation**.

- **K-Means Clustering for Task Optimization** (Sharma, 2025):
  - AI groups production tasks by resource dependencies, product type, or m**achine requirements**, minimizing transition delays.

- Ensures **efficient job sequencing**, reducing unnecessary machine setup.

- **ABC Analysis for Inventory Classification** (Skander Kacem, 2021).:
  - AI categorizes **SKUs based on demand patterns**, optimizing **stock levels and storage locations**.

- **Warehouse Location Clustering** (Qlik Help, 2024):
  - AI **groups inventory storage locations based on order frequency**, optimizing **retrieval paths and reducing travel distances**.

- **Hybrid AI Models for Warehouse Optimization** (Hassani et al., 2022):
  - **PSO optimizes warehouse storage allocation**, balancing **fast-moving vs. slow-moving inventory**.
  - **ACO & GA improve cargo location efficiency**, reducing **picking distances by 41.60%** and achieving **inventory reduction rates of 10.38%, 30.88%, 51.78%, and 88.49%** (Zhi Chen et al., 2025).

5.5.4. REAL-TIME ADAPTIVE SCHEDULING & SHOP FLOOR OPTIMIZATION

AI-driven **real-time scheduling systems** continuously process **production data, adjusting schedules based on live constraints**.

- **AI-Powered Scheduling Systems for Real-Time Adjustments** (PlanetTogether, 2024; Rootstock Software, 2024):
  - AI **reschedules tasks dynamically** when disruptions (e.g., machine failures, supply delays) occur.
  - AI-enabled **automated scheduling dashboards** provide real-time decision support.

- **NLP for Production Floor Optimization** (Ideamaker, 2024):
  - AI processes **operator feedback, production logs, and scheduling reports**, predicting inefficiencies.
  - **Sentiment Analysis detects workforce performance trends**, optimizing **shift planning and task assignments**.

- **Predictive AI for Demand-Based Scheduling** (Takyar, 2023):
  - NLP evaluates **historical sales data and market trends**, enhancing forecasting accuracy.
  - **Topic Modeling (LDA)** helps **categorize seasonal demand fluctuations**, ensuring production schedules align with market needs (Ihnatchyck, 2024).

5.5.5. DECISION INTELLIGENCE FOR SCHEDULING & CAPACITY PLANNING

AI-driven **decision-support systems** refine **production schedules and resource planning**.

- **AI Dashboards for Scheduling Optimization** (AIMMS, n.d.):
  - Provides **real-time scheduling updates, detecting bottlenecks and inefficiencies**.
  - AI **automates schedule refinement**, ensuring **minimal human intervention**.

- **NLP for Meeting Summarization & Action Tracking** (Ihnatchyck, 2024):
  - AI extracts **key scheduling decisions from production meetings**, ensuring accurate execution.
  - **Semantic Parsing** converts discussions into **structured action points**, aligning planning teams.

5.5.6. AI-DRIVEN TOOLS IN ICS & FCS

CS and ICS require AI-powered tools that **optimize production scheduling based on real-time capacity constraints and demand variability**.

AI-driven scheduling tools are increasingly being integrated into both approaches to better handle complex production scenarios and unexpected disruptions.(Li et al., 2024)

The selected tools were chosen for their ability to **adjust to real-world resource limitations, reduce bottlenecks, and enhance production efficiency**.

- **PlanetTogether**: Dynamic scheduling allowing quick adaptation to changes in demand, supply, or capacity constraints (PlanetTogether, n.d.).
- **Eyelit Technologies** – An **AI-powered finite capacity planning solution** that assesses **real-time resource constraints**, optimizing production schedules for **manufacturers and complex supply chains** (JBuglino, 2025).
- **SolveIT Software** – A **decision-support platform** using **AI-powered scheduling optimization**, enhancing **workflow flexibility, resource balancing, and production sequencing**. SolveIT's AI models address **both finite and infinite capacity constraints**, ensuring **efficient production scheduling** (Solveit, n.d.).
- **SkyPlanner APS**: An AI-powered **automated scheduling tool** that optimizes **production planning, sequencing, and finite capacity scheduling**, reducing **setup time and enhancing efficiency** (SkyPlanner, n.d.).

5.5.7. INDUSTRY APPLICATIONS OF AI-DRIVEN TOOLS IN ICS & FCS

Industries are **leveraging AI for capacity scheduling improvements**, focusing on **dynamic job sequencing, real-time scheduling, and warehouse efficiency**.

- **Toyota's AI-Driven Production Scheduling** (Google Cloud Blog, 2024):
  - AI-powered dynamic scheduling models optimize job sequencing and task prioritization.
- **Amazon's AI for Warehouse Scheduling & Fulfillment** (Qlik Help, 2024):
  - AI-powered warehouse clustering models optimize retrieval paths and picking sequences.
  - Reduces order processing time by 35% and improves on-time delivery rates.

5.5.8. CONCLUSION

AI-driven Finite & Infinite Capacity Scheduling (FCS & ICS) ensures real-time adaptability, workload balance, and production optimization, reshaping modern scheduling strategies.

Key Takeaways:

- **Machine Learning & Deep Learning** enhance **job sequencing and shift planning**.
- **Clustering & Optimization Algorithms** improve **warehouse efficiency and task grouping**.
- **NLP-powered automation** refines **workforce scheduling and production monitoring**.
- **ACO & PSO models** optimize **resource allocation, machine scheduling, and inventory control**.
- **Hybrid AI models** improve **capacity scheduling decision-making, reducing reliance on manual intervention**.

Future Trends:

- **AI-powered Digital Twins for scheduling simulations**.

- **Self-learning AI models for autonomous capacity scheduling**.
- **Explainable AI (XAI) for transparent decision-making in FCS & ICS**.

By integrating **AI into FCS & ICS workflows**, businesses **enhance production agility, reduce operational costs, and maintain resilience in dynamic manufacturing environments**

5.6. EXPECTED IMPROVEMENTS

The World Economic Forum's Annual Meeting 2025 in Davos highlighted a pivotal transformation in manufacturing and supply chains, driven by the convergence of sustainability imperatives and digital innovation. This new industrial paradigm positions sustainability, intelligence, and resilience as mutually reinforcing strengths (Ayesha Javed, 2025).

Digital Transformation in Manufacturing:

The Global Lighthouse Network has expanded to 189 manufacturing facilities worldwide, including 25 Sustainability Lighthouses. These facilities exemplify the profound impact of embracing digital transformation, achieving remarkable **productivity gains of 70%, reducing energy costs by 40%,** and **shortening time to market by 40%.** Advanced technologies such as analytics, artificial intelligence, and digital twins are enhancing human capabilities, enabling real-time production rerouting, predictive quality control, and energy optimization (Economictimes, 2025).

The **Global Lighthouse Network (GLN)** is an initiative launched by the **World Economic Forum (WEF)** in collaboration with **McKinsey & Company**. It recognizes **leading manufacturing sites** that successfully adopt and scale **Fourth Industrial Revolution (4IR) technologies** to drive **innovation, productivity, sustainability, and resilience** in manufacturing.

They are pioneering the integration of advanced technologies to achieve comprehensive objectives, from operational efficiency to environmental stewardship.

It includes **over 1,000 use cases** demonstrating the effectiveness of Industry 4.0 transformations (Dinu de Kroon , Enno de Boer and Rahul Shahani, 2025; Pabitra Kumar Chakrabarti, 2025).

In the dedicated domain of AI, early adopters of AI in SCM have achieved significant improvements, including a 15% reduction in logistics costs, a 35% enhancement in inventory levels, and a 65% increase in service levels (Maxime C. Cohen & Christopher S. Tang, 2024).

5.7. STUDY CASE – A SUPPLY CHAIN CONTROL TOWER

Let’s present the results of a research project conducted as part of a doctoral thesis, in 2022 in France, focused on the design and deployment of a Decision Support System (DSS) based on a control tower for managing risks in supply chains (Chenhui Ye et al., 2022).

This paper introduces a novel solution to the rising complexity and vulnerability of global supply chains: a **Supply Chain Control Tower** powered by a **Decision Support System (DSS)**. The goal is to improve how organisations identify, assess, and respond to supply chain risks - ensuring **greater resilience** and **collaborative decision-making** across stakeholders.

5.7.1. DESCRIPTION OF THE STUDY

5.7.1.1. CORE CONCEPTS

To understand the proposed system, it is crucial to first examine the foundational concepts of **supply chain risk** and **resilience**. These two dimensions form the backbone of the control tower's architecture.

5.7.1.2. SUPPLY CHAIN RISKS

Risks are broadly categorized into:

- **Internal risks**: such as machine breakdowns or IT failures
- **External risks**: like global crises or fluctuating demand

Further, risks can be:

- **Certain**: known sources (e.g., supplier failure)
- **Uncertain**: unpredictable events (e.g., pandemics)

This nuanced view of risk forms the basis for how the control tower models disruptions and responses.

5.7.1.3. SUPPLY CHAIN RESILIENCE

Following risk identification, the ability of a supply chain to **withstand and recover from disruptions -** its resilience - is key. This resilience is driven by:

- **Density**: number and proximity of nodes
- **Complexity**: degree of interconnection
- **Node Criticality**: importance of each node

These structural factors determine how severely a supply chain is impacted and how quickly it can bounce back.

5.7.1.4. THE CONTROL TOWER FRAMEWORK

Building upon the above concepts, the proposed system leverages a **Control Tower architecture** as a centralized hub for **risk monitoring, prediction, and response**.

5.7.1.4.1. COMPONENTS:

The control tower integrates:

- A **dashboard** centralizing real-time data
- **Digital risk sensors** embedded in existing SCM software (e.g., SAP)
- A **DSS module** for ranking mitigation strategies
- **Machine Learning algorithms** for predictive analytics

These components work together to transform supply chain risk management from a reactive to a **proactive, collaborative, and data-driven** process.

5.7.1.4.2. CAPABILITIES:

What sets this system apart is its **group decision-making functionality**, allowing multiple supply chain partners to jointly evaluate and select optimal strategies. Using **MCDM models**, the system ensures decisions are balanced, transparent, and weighted based on each firm's contribution to shared data.

5.7.1.5. RISK MANAGEMENT PROCESS

To operationalize these capabilities, the system digitizes the classic **four-stage risk management cycle**:

- **Risk Identification –** via manual alerts, sensor data, or ML forecasts
- **Risk Assessment** – using a knowledge base to analyse risk frequency, severity, and affected nodes
- **Risk Response –** supported by MCDM-based strategy evaluation
- **Risk Monitoring –** based on the **resilience triangle** (depth and duration of disruption)

Each step feeds seamlessly into the next, ensuring timely and effective mitigation.

5.7.1.6. RESULTS & SYSTEM PROTOTYPE

To validate the concept, the authors developed a DSS prototype called **"Module d'aide à la décision"**.

This prototype:

- Supports **10 decision models** (including 4 for group decisions)
- Accepts input via manual entry, CSV files, or external systems
- Will be integrated into the control tower for future testing

This module represents a critical step toward a **fully functional, real-time decision environment** for supply chain leaders.

5.7.1.7. KEY SCIENTIFIC CHALLENGES ADDRESSED

The control tower framework is not just technical—it addresses **collaboration challenges** that have long plagued supply chain coordination. Specifically, it:

- Identifies and interprets risks using **AI and IoT**
- Enables **shared decision-making** across enterprises
- Allocates **decision-making power proportionally** to data contributions
- Digitally models and evaluates **resilience strategies**

These innovations directly tackle long-standing issues of **information asymmetry and siloed decision-making**.

5.7.1.8. LIMITATIONS & FUTURE WORK

While promising, the authors acknowledge current **barriers to inter-company data sharing**, which may hinder adoption.

To address this, the team plans to:

- Conduct **experiments** with 10–20 real supply chain managers
- Simulate scenarios **with vs. without** the DSS-based tower
- Measure improvements in **performance, agility, and resilience**

These efforts aim to empirically validate the framework and refine its collaborative mechanisms.

5.7.2. APPLICATION IN SCM 4.0

The **DSS-based Supply Chain Control Tower** can be applied at **multiple levels of the Supply Chain Management (SCM) hierarchy**, but is particularly impactful at the **tactical and strategic levels**, with some real-time support at the operational level.

5.7.2.1. STRATEGIC LEVEL – NETWORK DESIGN & RISK POLICY

Use Cases:

- Designing resilient supply chain networks (e.g., location and criticality of nodes)
- Developing long-term **risk mitigation policies**
- Establishing **collaboration agreements** and data-sharing frameworks between partners
- Prioritizing investments in resilience (e.g., redundant suppliers, nearshoring)

Role of the Control Tower:

- Assists C-level (C for “Chief”) executives and risk managers in making informed, high-impact decisions
- Simulates risk scenarios and compares long-term strategies using MCDM models

5.7.2.2. TACTICAL LEVEL – PLANNING & PREPAREDNESS

Use Cases:

- **Mid-term planning** of production, sourcing, and distribution with risk-awareness
- Evaluating suppliers not just on cost but also **resilience and risk profiles**
- Implementing **early warning systems** and scenario planning
- Allocating **inventory buffers** or rerouting plans based on predicted disruptions

Role of the Control Tower:

- Provides **predictive risk insights** via AI and data integration
- Enables group decision-making to select the best alternative mitigation strategies across functions and partners
- Facilitates **collaborative contingency planning**

5.7.2.3. OPERATIONAL LEVEL – EXECUTION & MONITORING

Use Cases:

- Real-time monitoring of key performance indicators (KPIs)
- Alerting for **immediate disruptions** (e.g., delayed shipments, supplier outages)
- Coordinating emergency responses across entities

Role of the Control Tower:

- Uses **digital sensors and data feeds** to detect anomalies in real time
- Triggers alerts and **proposes predefined response strategies**
- Supports **daily operational decisions**, especially during disruptions

Note: While it’s not built for day-to-day task automation (like WMS or TMS systems), it enhances **operational decision-making during exceptional events**.

6. IMPACT OF SCM 4.0 ON SMES

Emerging digital technologies such as **Artificial Intelligence (AI), Internet of Things (IoT), Edge vs. Cloud-based computing, and AI-driven solutions** are reshaping **Supply Chain Management (SCM)** at different levels, including **Profit Planning, Sales & Operations Planning (S&OP), Master Production Scheduling (MPS), Material Resource Planning (MRP), and Finite & Infinite Capacity Scheduling (FCS/ICS)**.

While large corporations have been early adopters of Supply Chain Management 4.0 (SCM 4.0), **Small and Medium Enterprises (SMEs)** face both significant challenges and promising opportunities in embracing this transformation. Although digitalization is widely recognized as essential for improving efficiency and competitiveness, it requires the integration of technologies such as **cloud computing, artificial intelligence, data analytics, and automation** to enhance decision-making and streamline supply chain operations.

In this journey of digitalisation, many companies face challenges (Sam Phipps, 2025).

- **Outdated Systems**: Approximately 42% of companies still rely on legacy solutions that need replacement.
- **Manual Processes**: Around 67.4% of supply chain managers primarily use Excel spreadsheets for management.
- **Data Quality**: Only 3% of companies' data meets basic quality standards.
- Shortage of skilled workforce (MarketsandMarkets, 2025).

Among internal challenges SMEs face when adopting emerging digital technologies in Supply Chain Management (SCM), the following key obstacles have been highlighted by (Hussein Kamaldeen Smith, 2024; Restrepo-Morales et al., 2024):

- **Financial Constraints:** SMEs often lack the financial resources necessary to invest in digital infrastructure and technologies. High costs associated with digital transformation can be prohibitive, making it difficult for these enterprises to adopt new systems.
- **Limited Technological Expertise:** Many SMEs do not possess the in-house expertise required to implement and manage advanced digital solutions. This skills gap can hinder the effective adoption of technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT).
- **Resistance to Change:** There can be a reluctance among employees and management to alter established processes. This resistance to change can slow down or even prevent the integration of new technologies within the supply chain.
- **Inadequate Infrastructure:** SMEs may lack the necessary infrastructure to support digital technologies, such as reliable internet connectivity and modern hardware, which are essential for effective SCM digitalization.
- **Insufficient Management Support:** Without strong commitment from leadership, digital initiatives may lack direction and resources, leading to unsuccessful implementation.
- **Integration with Existing Systems:** Merging new digital technologies with legacy systems can be complex and costly, posing significant challenges for SMEs aiming to modernize their supply chain operations.
- **Data Security Concerns:** Implementing digital technologies introduces risks related to data security and privacy. SMEs may struggle to establish robust cybersecurity measures to protect sensitive supply chain information.

6.1. INTERNAL SME CHALLENGES ADOPTING EMERGING DIGITAL TECHNOLOGIES

The following section provides a detailed analysis of the internal barriers briefly outlined above, offering deeper insight into the specific challenges SMEs face when adopting emerging digital technologies in supply chain management.

6.1.1. DIGITAL MATURITY AND ADOPTION RATES

6.1.1.1. OVERVIEW

According to Eurostat (2021), only 3% of SMEs in the EU had achieved a very high level of digital intensity. Despite the acceleration brought by the COVID-19 pandemic, **the majority of SMEs remained at low (34%) or very low (45%) levels** of digitalization, indicating that digital transformation had largely stalled across this segment (Amanda St L Jobbins, 2023).

In the survey **Published by Vodafone Europe in early 2023**, based on a **survey of 3,358 SMEs** across 11 European countries, including 2,677 in 9 EU Member States the following key figures have been highlighted (Vodafone Europe, 2023).

- **82%** of SMEs and SoHos (1–9 employees) consider digitalisation **important**.
- **Only 3%** of SMEs in the EU have a **very high level** of digital intensity
- **46%** of SMEs expect **cost savings** as a top benefit of digitalisation.
- **40%** cite **cybersecurity improvement** as a major expected benefit.
- 35% hope to expand into new markets or sales channels.
- **25%** of SMEs are interested in **IoT solutions** through funding schemes.
- **Only 15.5%** of small firms provide **internal ICT training** (vs. 61.6% of large firms (OECD, 2021).

While simpler technologies - such as maintaining a company website - are now widely adopted even among smaller firms, the uptake of more advanced IT solutions remains limited. In fact, SMEs consistently lag behind larger companies in adopting both basic technologies, like internet connectivity, and more sophisticated systems, such as cloud computing.

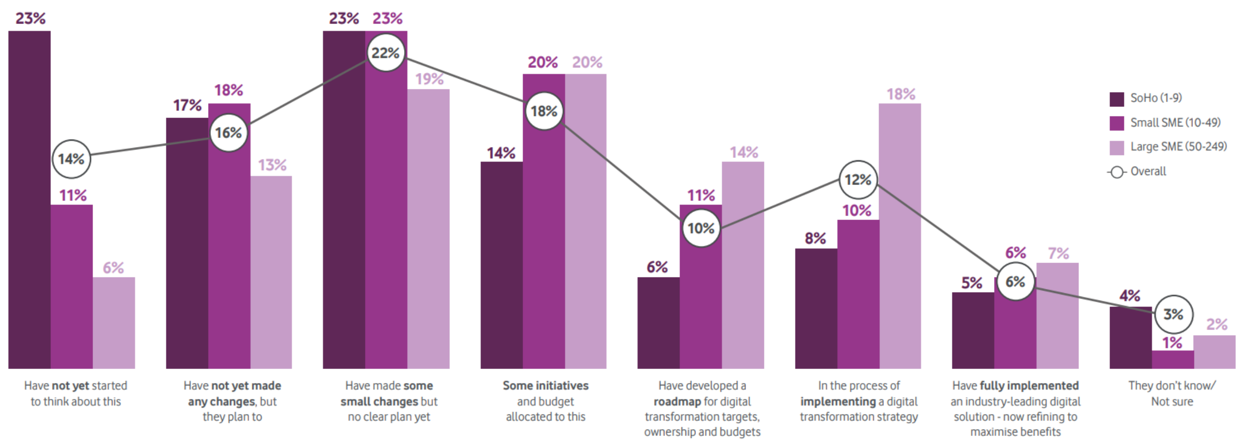

Figure 6. Between SME segments, the larger the organisation, the more progress they have made in their digital journey (Vodafone Europe, 2023)

- In 2022, **69% of SMEs** in the EU reached a **basic digital intensity level**, versus **98% for large enterprises**. (World Economic Forum, 2023b)
- In 2021, **only 8% of EU companies** were using **Artificial Intelligence**, with **large companies more likely to adopt** than SMEs. (World Economic Forum, 2023b)
- **Cloud computing** was used by **40% of SMEs**, versus **72% of large companies** in 2021. (World Economic Forum, 2023b)

6.1.1.2. SUPPLY CHAIN DIGITALISATION

Actual adoption - particularly of advanced tools like AI - remains limited due to capability gaps, insufficient internal resources, and unrealised returns on investment.

Focussing on SCM area, the (Vodafone Europe, 2023) survey provides such key figures:

- **25%** of SMEs are interested in **IoT solutions** through funding schemes.
- **16%** of large SMEs consider **IoT** the **most appealing** digital solution to adopt.
- **46%** of SMEs cite **cost efficiency** (including supply chain optimisation) as their top digitalisation benefit.

In addition, the policy paper (OECD, 2021) **provides these key figures:**

Current Status

- **AI adoption among SMEs remains very limited**, mainly due to a combination of **low awareness**, **lack of digital skills**, and **financial/resource constraints**.
- **Access to data and scalable funding** is critical for successful AI uptake, but most SMEs do not have these conditions in place.
- There's a **knowledge and capability gap** between digital "frontier firms" and traditional SMEs, which widens over time without intervention.
- Despite **93% of planners** expressing willingness to adopt new technology tools, only **40%** have actually transitioned to using them, highlighting a gap between intent and implementation (Kevin Miceli, 2024).
- **69% of operations and supply chain officers** reported that their technology investments have not fully achieved the anticipated outcomes (ECI Software Solutions, 2024).

AI in Practice

- AI is still **rarely integrated into core SME SCM processes**. When it is used, it's often through external platforms or service providers.
- **Only 12% of SMEs** reported using big data, which is often a prerequisite for AI tools, compared to **33% of large firms**.
- **15.5% of small firms** provide ICT training to non-ICT staff, a critical factor for enabling AI adoption.

6.1.1.3. GREEN TRANSITION & SUSTAINABILITY

As far as the green transition is concerned, this survey mentioned:

- **45%** of SMEs and SoHos believe it's their **responsibility** to drive sustainability in their sector.
- **40%** are already factoring **climate adaptation** into business planning.
- **Nearly 25%** of European SMEs are **already offering green products or services**.
- EU estimate: technology could reduce **global emissions by up to 15%**, **7 times more** than the emissions created by the ICT sector itself.

6.1.2. TECHNOLOGICAL INTEGRATION BARRIERS

The adoption of emerging digital technologies by SMEs is often hindered by internal challenges, particularly those related to technological integration, as detailed below (Khairen Niza Mefid & Fitria - Ridhaningsih, 2024).

- SMEs often hesitate to adopt advanced technologies like AI or ERP due to **lack of technological expertise**. This is described as a key **technological hurdle** preventing effective implementation.
- **Interoperability issues** between legacy systems and new technologies are common, especially when attempting to integrate ERP and AI. This is worsened by **poor collaboration between departments** and low integration between management and operations.
- SMEs also face **inadequate infrastructure** and **low standardization of data exchange interfaces**, which creates operational silos and blocks real-time collaboration.

6.1.3. TALENT AND SKILLS SHORTAGES

One of the most significant barriers SMEs face in adopting emerging digital technologies across supply chain processes is the **shortage of skilled talent and digital literacy**.

- A **lack of qualified staff** and digital training is frequently cited as a major barrier in SME adoption of digital supply chain tools. This shortage is often linked to the **existing workforce's lack of experience** with new technologies (Khairen Niza Mefid & Fitria - Ridhaningsih, 2024).
- Skills shortages limit SMEs' ability to operate or even evaluate digital technologies like cloud ERP or IoT (Khairen Niza Mefid & Fitria - Ridhaningsih, 2024).
- SMEs often **lack in-house AI and data analytics expertise**, making the adoption of **predictive analytics, IoT sensors, and AI-driven demand forecasting difficult** .
- **Hiring AI and cloud computing experts is costly and highly competitive** (Catherine Early, 2024).

6.1.4. CYBERSECURITY CONCERNS

C**ybersecurity concerns present a critical barrier** to digital technology adoption among SMEs. As they integrate tools like **AI, IoT, and cloud-based ERP**, SMEs often lack the **formal cybersecurity frameworks, technical expertise, and dedicated teams** needed to safeguard sensitive data and systems. This makes them **especially vulnerable to data breaches, ransomware attacks, and privacy violations**, despite high internet connectivity rates across the sector:

- SMEs face **privacy and data protection issues** when adopting technologies like AI or cloud-based ERP. The **lack of cybersecurity readiness** makes them vulnerable to attacks (Khairen Niza Mefid & Fitria - Ridhaningsih, 2024).
- Many SMEs lack **formal cybersecurity frameworks**, despite 94% having internet access (EU average - (World Economic Forum, 2023b))
- **IoT-driven SCM introduces cybersecurity risks**, as connected sensors and cloud platforms can be **vulnerable to cyberattacks**.
- Many SMEs lack dedicated **cybersecurity teams**, making them more susceptible to **data breaches and ransomware attacks** (CISA, n.d.).

6.1.5. CHANGE MANAGEMENT & RESISTANCE

Another major hurdle in the digital transformation of SMEs is **organisational change management and internal resistance**, despite the potential benefits of AI, IoT, and cloud-based SCM tools (Khairen Niza Mefid & Fitria - Ridhaningsih, 2024; World Economic Forum, n.d.).

- Organisational **resistance to change** is a recurring barrier. It includes reluctance from employees, fear of job disruption, and **absence of support from management**.
- The **lack of a clear understanding of why digital tools are being implemented** within the company often leads to failure of integration efforts prefering **manual processes** for planning and procurement (Khairen Niza Mefid & Fitria - Ridhaningsih, 2024; World Economic Forum, n.d.).

6.1.6. FINANCIAL CONSTRAINTS

SMEs often struggle to allocate sufficient budgets for **AI-driven SCM solutions, IoT deployments, and cloud-based ERP upgrades** (Khairen Niza Mefid & Fitria - Ridhaningsih, 2024; Vodafone Europe, 2023).

- Cloud computing reduces infrastructure costs, but **pay-as-you-go models can still be costly for SMEs**.
- **High initial costs** and **limited financial resources** are among the top inhibitors to digital adoption. These barriers are particularly difficult for SMEs that operate with constrained budgets.
- SMEs struggle to secure external funding for technology investments and frequently lack access to **targeted public funding schemes**.

6.2. IMPACT ON ORGANISATIONS

The adoption of digital technologies such as AI, IoT, and cloud/edge computing is reshaping supply chain organisations across multiple dimensions. These technologies do not merely enhance technical capabilities; they transform decision-making, collaboration, culture, and operational structure.

6.2.1. CULTURAL SHIFT TOWARD AGILITY & SCALABLE INNOVATION

Digital tools enable rapid experimentation, iterative prototyping, and agile execution within supply chain teams (Gartner, n.d.; Vinay Rajani & Preeti AryaCrossman, 2023). **Impacts:**

- Adoption of test-and-learn mindsets, 8–12 week pilots to refine use cases and stakeholder alignment.
- Creation of digital innovation pods or pilots to drive transformation.

6.2.2. SHIFT FROM FUNCTIONAL SILOS TO CROSS-FUNCTIONAL COLLABORATION

Digital platforms (e.g., cloud-based ERP, planning suites) and connected technologies (IoT, AI) enable seamless data sharing across departments. This fosters end-to-end process integration and visibility (Ning & Yao, 2023). **Impacts:**

- Functional boundaries give way to cross-functional digital teams.
- Higher levels of process standardisation, transparency, and synchronicity.

6.2.3. ENHANCED STAKEHOLDER ENGAGEMENT & KNOWLEDGE MANAGEMENT

AI-powered assistants (e.g., chatbots, LLMs) support communication, summarise meeting outcomes, and help structure stakeholder inputs (Vinay Rajani & Preeti AryaCrossman, 2023). **Impacts:**

- Structured, timely input across sales, planning, and operations.
- Automated meeting summaries and knowledge storage improve continuity and decision traceability.

6.2.4. FASTER DECISION-MAKING & AUTOMATED PLANNING

Real-time data (IoT), predictive analytics, and AI-supported planning enable more agile decision-making and scenario testing (Gartner, n.d.; Vinay Rajani & Preeti AryaCrossman, 2023). **Impacts:**

- Shortened planning cycles (e.g., S&OE loops).
- Automation of routine tasks frees up time for strategic activities.

6.2.5. SCENARIO-BASED CULTURE & RESILIENCE ORIENTATION

AI and digital twins empower supply chain organisations to simulate disruptions and stress-test decisions (Zhao et al., 2023). **Impacts:**

- Proactive risk management becomes embedded in planning.
- Culture shifts toward readiness, flexibility, and system thinking.

6.2.6. EXTERNAL COLLABORATION & PLATFORM ECOSYSTEMS

Cloud and API-based systems allow firms to integrate data and processes with suppliers, 3PLs, and ecosystem partners (T. Leigh Buehler, 2023). **Impacts:**

- Enhanced transparency and collaboration across supply networks.
- Redefinition of supply chain boundaries around shared platforms.

6.2.7. DATA DEPENDENCY & GOVERNANCE REINFORCEMENT

With AI and real-time analytics at the core of SCM decisions, data quality, access, and governance become central (Zhou et al., 2024). **Impacts:**

- Formal data stewardship roles and governance frameworks.
- Increased scrutiny on interoperability and data reliability.

At the same time, a recent survey highlighted the weaknesses in the way SMEs are organised to anticipate this revolution (World Economic Forum, 2023a):

6.2.7.1. LACK OF DESIGNATED ROLES AND SKILLS

60–63% of SMEs surveyed reported that they **do not have a chief data officer (CDO), chief privacy officer (CPO), or chief information security officer (CISO)**. This absence of defined roles **undermines the strategic management of data** and the ability to comply with privacy, security, and regulatory obligations.

6.2.7.2. LOW DATA LITERACY AND CAPACITY

64% of SMEs struggle to **effectively use data from their systems**. **74%** struggle to **extract value from data investments** due to poor integration, lack of strategy, and skills shortages. **54–55%** of SMEs struggle to maintain and locate data.

6.2.8. CYBERSECURITY AWARENESS & INFRASTRUCTURE RESILIENCE

As supply chains adopt interconnected digital systems (IoT, cloud platforms, AI-driven planning), the risk of cyber threats rises. Cybersecurity becomes not just an IT concern but a core organisational priority in SCM (Masip-Bruin et al., 2021; OECD, 2021). **Impacts:**

- Development of cross-functional **cyber-risk management teams** in supply chain operations.
- Investment in **cyber-resilience protocols** for cloud platforms, API integrations, and IoT networks.
- Rise of **training needs** for non-IT staff on cyber hygiene and data access governance.

6.2.9. REALLOCATION OF WORKFORCE TASKS AND SKILLS

AI, automation, and cloud solutions change workforce expectations, shifting emphasis to digital supervision, exception handling, and strategic foresight (Sarah Shelley, 2024). **Impacts:**

- Emergence of hybrid roles (e.g., supply chain analysts with digital competencies).
- Greater need for continuous upskilling and cross-functional digital fluency.

6.3. IMPACT ON WORKFORCE

While digitalisation offers undeniable operational advantages, it simultaneously brings complex implications for the workforce in SMEs, particularly within Supply Chain Management (SCM). These include evolving skill demands, significant job transformation, and the urgent need for proactive reskilling, change management, and cultural adaptation. The convergence of IoT, AI, and cloud/edge computing is reshaping not just how supply chains operate, but also how people work within them.

6.3.1. DIGITAL SKILLS GAP & TALENT SHORTAGES

The integration of AI, IoT, and cloud technologies into SCM processes has triggered an escalating demand for professionals proficient in data science, automation, cloud architecture, and digital process optimization. However, SMEs often face deeper digital skills shortages compared to large enterprises, stemming from limited training resources, budget constraints, and difficulty attracting digital talent.

6.3.1.1. EVOLVING SUPPLY CHAIN COMPLEXITIES AND SKILL SHORTAGES

As supply chains become more intricate, there's a heightened need for expertise in advanced technologies. However, many organisations face challenges in attracting and retaining talent proficient in these areas. A recent article highlights that supply chain leaders are struggling to find qualified candidates in data analytics and AI, exacerbating the talent shortage in the field (Jeremy Tiffin, 2025).

6.3.1.2. AI-POWERED SCM TOOLS AND SME WORKFORCE LIMITATIONS

The adoption of AI-driven tools in SCM necessitates competencies in data science, cloud computing, and automation. Unfortunately, many SME employees lack these specialized skills, hindering effective implementation. A study examining the impact of AI on global SCM underscores that challenges related to data quality, cost of implementation, and workforce adaptation are significant barriers to AI adoption in supply chains (Subharun Pal et al., 2025).

6.3.2. SKILLS TRAINING & MISALIGNMENT IN SYSTEM IMPLEMENTATION

While **implementing new Information Systems (IS)** such as AI-powered forecasting tools, IoT-based tracking, and predictive analytics **should ideally involve employee training**, in practice, **many SMEs fail to provide structured upskilling during deployment**.

"Too often, digital tools are deployed without sufficient attention to employee onboarding or upskilling, creating usage gaps and poor adoption rates." (World Economic Forum, 2023a)**.**

6.3.2.1. WORKFORCE UNPREPAREDNESS UNDERMINES ROI

Many SMEs invest in ERP, cloud, or AI platforms without developing the **human capabilities to manage or extract value from these tools**. According to Eurostat (2023), **SMEs significantly lag behind large enterprises in digital skills**, with only 69% reaching a basic digital intensity level versus 98% of large firms (Eurostat, 2023).

6.3.3. EMPLOYEE TRAINING NEEDS & LEARNING CURVE

SMEs must invest in **upskilling programs** to enable workers to **leverage AI-powered forecasting, IoT-based tracking, and predictive analytics**.

6.3.4. RESISTANCE TO AI & AUTOMATION ADOPTION

Employees fear **job loss** due to automation, leading to **resistance in adopting digital tools**.

Many SMEs lack a **change management strategy** to facilitate digital adoption in their workforce.

6.3.5. CYBERSECURITY AWARENESS GAPS

Increased digitalization **exposes SMEs to cyber risks**, but **employees may not be trained in cybersecurity best practices**. Human error remains **one of the top causes of cybersecurity breaches**, requiring SME-specific training programs.

These workforce challenges highlight the **urgent need for SMEs to invest in AI adoption strategies, employee upskilling, and change management** to ensure a **smooth transition into digitalized SCM processes**.

6.4. RESULTS OF SCM SURVEY SENT TO SMES

6.4.1. OVERVIEW OF THE SURVEY

To assess the adoption and impacts of **emerging digital technologies (Industry 4.0)** and **green transition trends** on **Supply Chain Management (SCM 4.0)** among Small and Medium-sized Enterprises (SMEs), a survey has been conducted across European countries France, Germany, Slovenia, Italy with the participation of Turkey.

The survey gathered insights on **company size**, **primary industry sector**, **current SCM practices**, **technological adoption**, **workforce impact**, and **future perspectives on SCM 4.0**. The results provide interesting data on the challenges and opportunities the SMEs involved face in integrating SCM 4.0 into their operations.

A total of 176 SMEs have been invited to participate, with 18 companies responding providing the following origin and size distribution:

6.4.2. ANALYSIS AND RELIABILITY OF THE SURVEY RESULTS

With a response rate of 10% out of a total of 176 requests for information sent to SMEs, the results indicate a trend that could be taken into consideration (see statistics provided in the chapter on methodology) even if the sample can't be considered as 'generalisable'.

6.4.3. GENERAL INFORMATION ON THE SURVEYED SMES

6.4.3.1. SIZE DISTRIBUTION OF RESPONDING SMES

While the survey collected valuable insights from 18 SMEs across five countries, the sample size remains relatively limited considering the total population of 176 SMEs initially targeted. The distribution is also uneven, with a significant concentration of responses from Turkey (7 responses) and France (6 responses), while countries such as Germany (2), Slovenia (2), and Italy (1) are underrepresented.

This imbalanced geographical participation may affect the representativeness of the findings, particularly when drawing cross-country conclusions or identifying patterns across diverse industrial contexts. Moreover, with only about 10% of the targeted SMEs responding, the statistical reliability of the survey should be interpreted with caution (.

That said, the collected responses still offer qualitative value, especially when considered alongside complementary data sources or expert interviews.

Table 7. SME Survey Response Distribution by Country

Toward	Country	Number of Companies	Number of answers
SMEs	FR	118	6
	GER	39	2
	IT	1	1
	SL	11	2
	TR	7	7
Total SMEs		**176**	**18**

6.4.3.2. SIZE OF ORGANISATIONS

The survey categorised SMEs into four size groups based on the number of employees:

- Micro (1-9 employees)
- Small (10-49 employees)
- Medium (50-249 employees)
- Large (250+ employees) (although large companies are not typically SMEs, they were still included in some responses)

Small and medium-sized companies are the most representative in this survey.

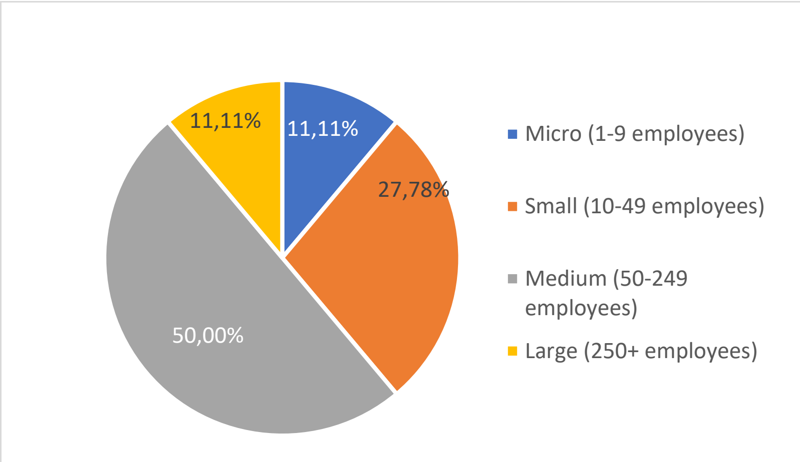

Figure 7. Size Distribution of Responding SMEs

6.4.3.3. SIZE OF ORGANISATIONS PER COUNTRY

Main contributors, France and Turkey have representation across small and medium categories.

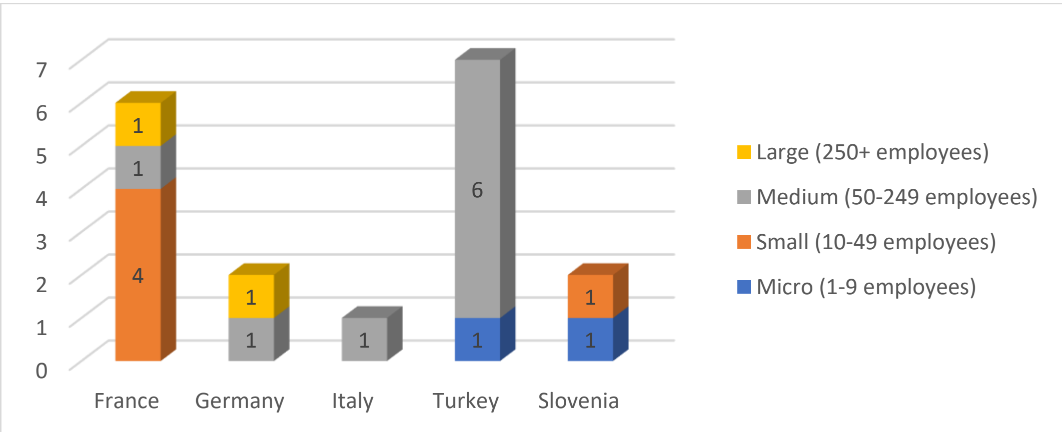

Figure 8. Size of organisations per country

6.4.3.4. SIZE OF ORGANISATIONS WHICH ANSWERED PER PRIMARY INDUSTRY SECTOR

The participating companies **belonged to various sectors**, mainly in **Chemical industry, Aerospace and Defence:**

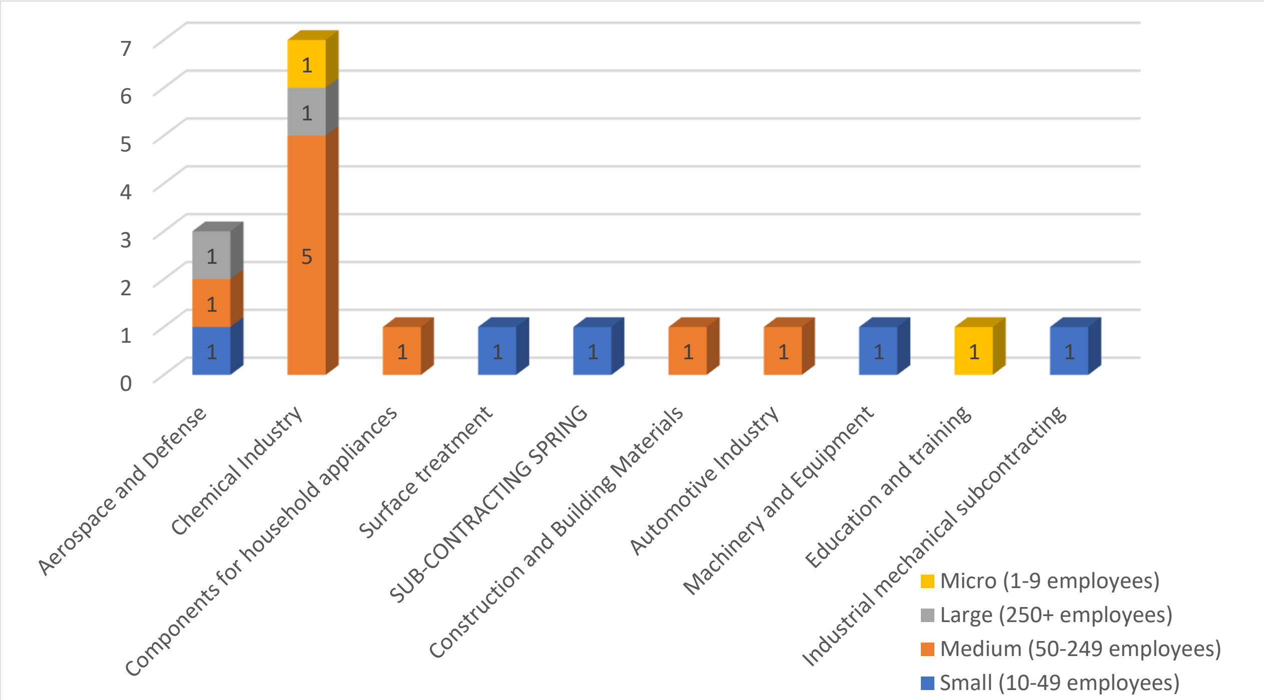

Figure 9. Size of organisations which answered per primary industry sector

6.4.3.5. ROLES WITHIN THE COMPANY

The chart below provides an overview of the **roles of respondents within their companies**, categorized by functional domain and company size. It illustrates a diverse representation across organisational roles with a balanced mix of company sizes, including **small**, **medium**, **large**, and **micro-enterprises**. This diversity enhances the relevance of the insights gathered, as it reflects multiple perspectives from different levels of responsibility and sectors within the SMEs surveyed.

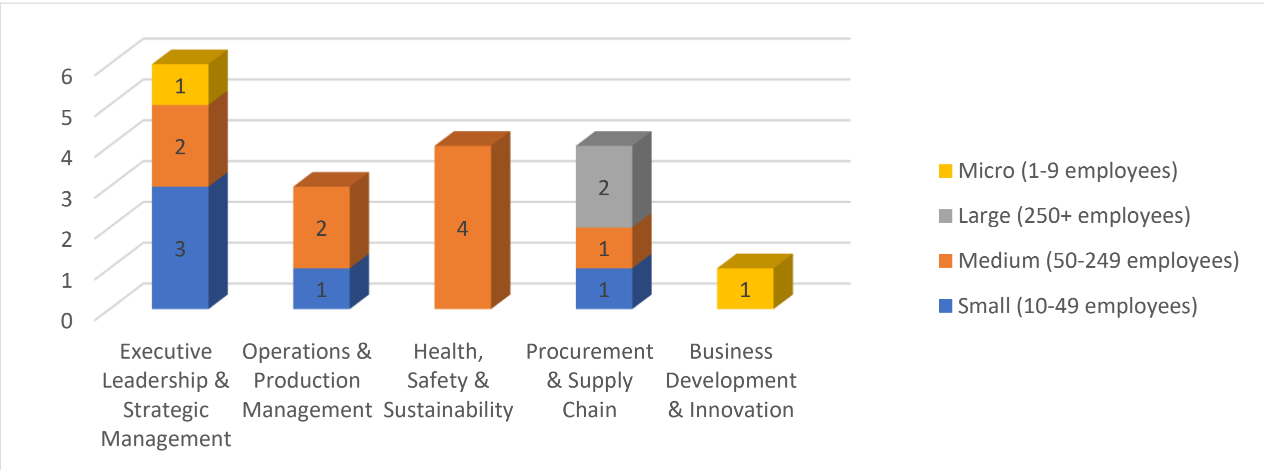

Figure 10. Roles within the company

6.4.4. CURRENT STATE OF DIGITAL SYSTEMS ADOPTION IN SMES

When it comes to the areas of digital supply chain management systems currently implemented in SMEs, company size clearly influences the degree of adoption, with small companies leading the way in integration efforts, with 80% to 100% fully or partially integrating tools such as MRP, S&OP/MPS, shop floor planning and data analysis, followed by medium-sized companies with an average of between 30% and 50% for digital supply chain management systems and data analysis tools.

Micro-enterprises often trail behind. The sample of large companies is too restrictive to be significant.

(To enhance readability and account for variations in sample sizes across company categories, the percentages represent the relative proportion within each company size group.)

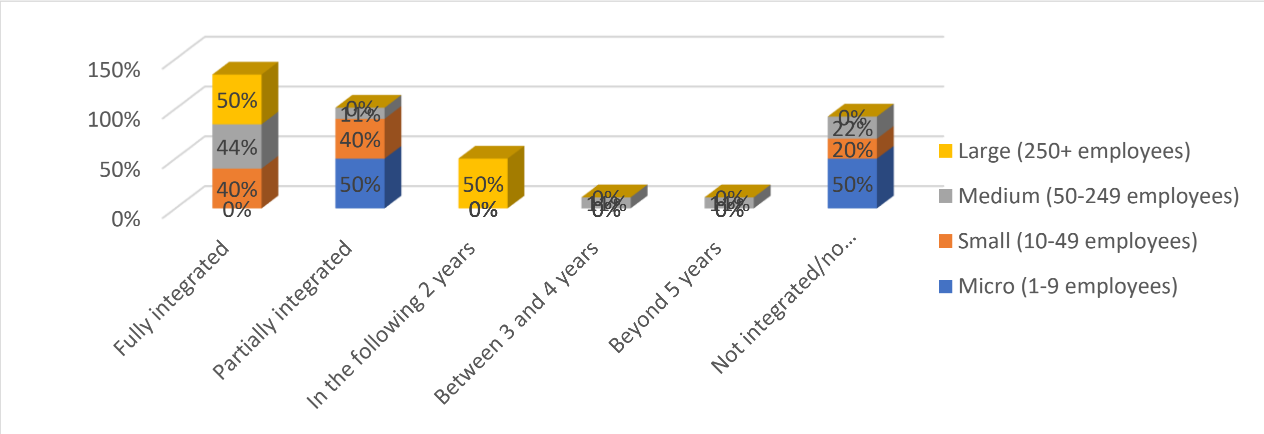

Figure 11. Basic ERP System (Enterprise Resource Planning for managing inventory, orders, and production) digital systems adoption

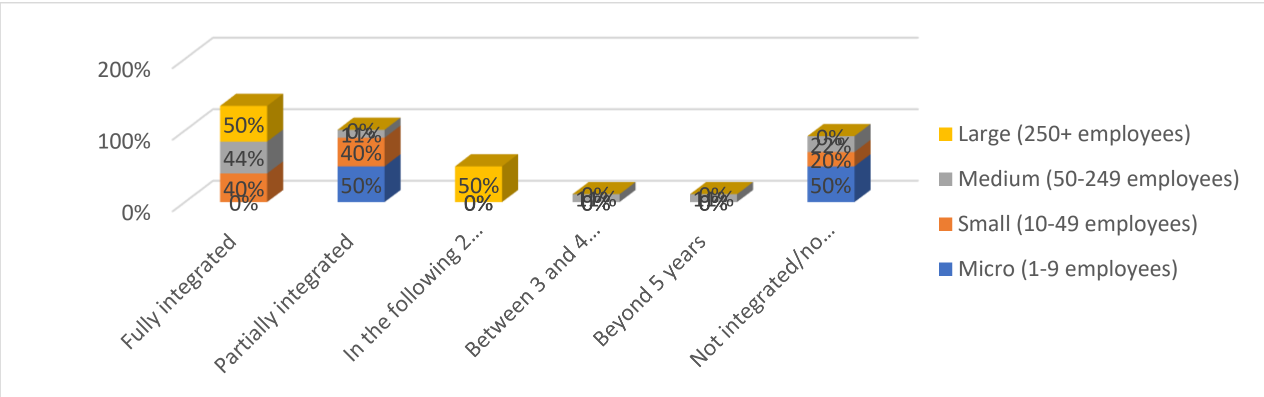

Figure 12. Industrial and commercial planning (Sales and Operations Planning (S&OP) / Master Planning Schedule (MPS)) digital systems adoption

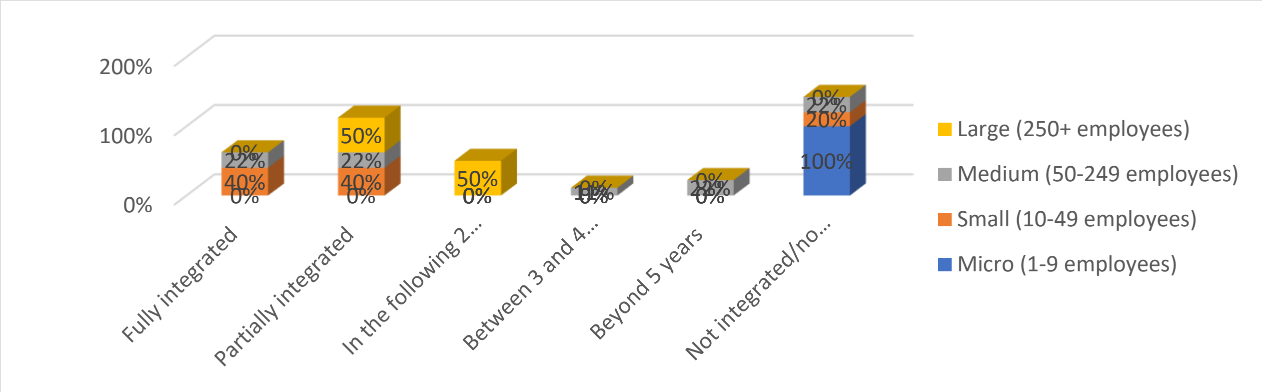

Figure 13. Shop floor scheduling digital systems adoption

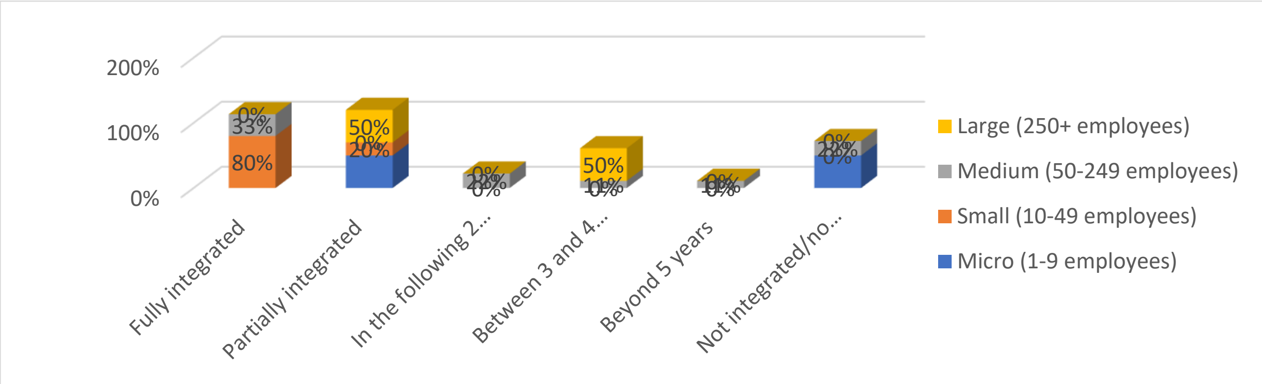

Figure 14. Data Analytics Tools (dashboards, KPI tracking, data visualization) digital adoption

6.4.5. PERCEPTION OF EMERGING TECHNOLOGIES 4.0 IN IMPROVING SUPPLY CHAIN PROCESSES

Based on the responses to the question *"How important do you consider the role of the following emerging technologies 4.0 in improving Supply Chain processes within your organisation?"*, we can draw a strong awareness and perceived importance of emerging technologies among medium-sized companies, with most of them considering these technologies either mandatory or important for improving supply chain processes.

Surprisingly, at least one large company sees these technologies as merely "Beneficial but Not Essential", and another even reports being "Not familiar" with them. This indicates that awareness and strategic alignment with digital transformation is not yet universal, even among larger enterprises.

At the same time, micro and small companies show a diverse range of perceptions, from critical recognition to unfamiliarity—highlighting the need for targeted outreach, education, and support to enable broader adoption across the SME spectrum.

(To enhance readability and account for variations in sample sizes across company categories, the percentages represent the relative proportion within each company size group.)

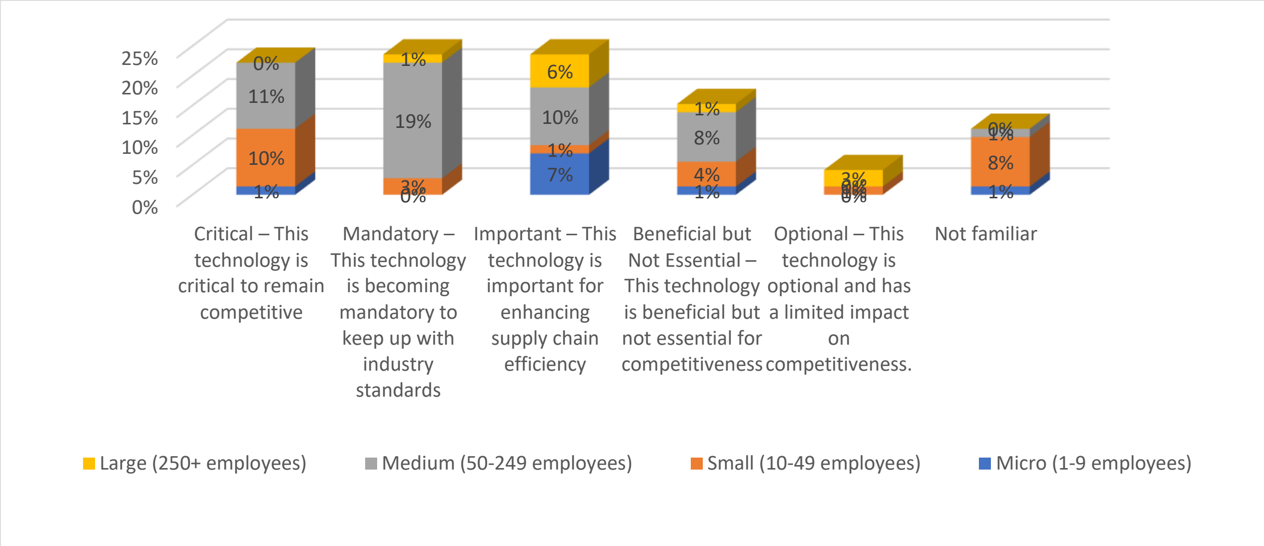

Figure 15. Role of emerging technologies 4.0 in improving Supply Chain processes

In detail, the following synthesis provides a cross-analysis of how SMEs of different sizes perceive the importance of key emerging technologies and green transition - such as IoT, AI, Cloud Computing, Cybersecurity, and Green Technologies - for improving supply chain processes. It highlights varying levels of awareness, adoption, and strategic prioritization, offering insights into digital maturity across company sizes.

1. Internet of Things (IoT – sensors, connected machines for real-time monitoring)

- **Micro (1–9 employees)**: Very limited adoption. One company reports being unfamiliar, and none consider it "critical" or "mandatory."
- **Small (10–49 employees)**: 40% of companies see it as "critical," but 40% of others are unfamiliar, showing a **wide gap in awareness**.
- **Medium (50–249 employees)**: Strong recognition: 66% of "critical", "mandatory" and "important". IoT is perceived as an **essential enabler**.
- **Large (250+ employees)**: 50% consider it "important," 50% "not familiar," showing **mixed engagement** despite assumed capacity.

2. Artificial Intelligence (AI – forecasting, analytics, optimization)

- **Micro**: 100% consider as "important" — showing interest but **not yet strategic usage**.
- **Small**: 40% see it as "critical" or Important and 40% are unfamiliar - indicating **polarized maturity levels**.
- **Medium**: 77% of "mandatory" or "important," and 23% "beneficial but not essential" - **AI is gaining strategic relevance**.
- **Large**: 50% "important," 50% "beneficial but not essential" - adoption seems **more cautious or fragmented**.

3. Cloud-Based Computing (data sharing, visibility)

- **Micro**: 50% see it as "not essential," 50% as "important" - **moderate understanding**, low strategic integration.
- **Small**: 60% consider it "critical" or "mandatory," others "non-essential" or "unfamiliar" - **diverse levels of adoption**.
- **Medium**: Strong adoption: 77% "critical", "mandatory" or "important," 23% "non-essential" - **broad and solid integration**.
- **Large**: 50% "important", 50% "not essential" - seems to be used but **not viewed as transformational**.

4. Cybersecurity Measures

- **Micro**: 50% see it as “critical,” 50% as “important” - awareness is **clearly present**.
- **Small**: 60% “critical” and “mandatory” others see it as “optional” or are unfamiliar - **need for reinforcement**.
- **Medium**: Dominant agreement: 100% “critical”, “mandatory” and “important” - **high maturity and strategic alignment**.
- **Large**: 50% “mandatory” 50% “important” - **few responses**, but no signs of underestimating importance.

5. Green Technology / Awareness

- **Micro**: 50% “critical,” 50% “not essential” - **split perception**, with room for awareness-building.
- **Small**: Mixed results: 40% “critical” or “important,” 40% “non-essential,” 20 “unfamiliar” - **varying engagement**.
- **Medium**: 100% “critical”, “mandatory” or “important” - **very strong commitment to sustainability**. This may be consistent with the predominance of the chemical medium size companies represented in this survey.
- **Large**: 50% “non-essential”, 50 “unfamiliar” - **fragmented perspective**, despite likely regulatory exposure.

6.4.6. ADOPTION OF EMERGING TECHNOLOGIES 4.0

Based on the responses to the question *"Which emerging technologies 4.0 are you currently using in Supply Chain Management (SCM), or planning to adopt in the near future? And at which level of your SCM processes?"*, the chart reveals the following key insights:

- **Operations Execution & Scheduling:** This is by far the most active area for technology adoption, with **34 mentions** across all technologies.
    - **IoT (7)**, **Cloud (8)**, and **AI (9)** lead the way, indicating a strong focus on real-time control, flexibility, and data-driven decision-making on the shop floor.
    - This reflects a clear **operational priority** for automation and responsiveness in day-to-day supply chain execution.
- **Not Integrated / No Plans to Adopt:** we can identify the same significant number of 34 mentions of **no current or near-future adoption plans**, especially for **AI (9)**, **IoT (6)**, and **Cybersecurity (6)**.
    - This indicates **persistent barriers** such as complexity, cost, or lack of clarity in ROI across certain sectors or company sizes.
    - It may also reflect **prioritization of other areas or lack of internal readiness**.
- **Data Analytics Tools:** also heavily adopted (**26 mentions**), particularly for **AI (7)**, **IoT (5)**, and **Cloud (3)**.
    - This highlights how **performance monitoring and KPI tracking are already being enhanced** through digital tools.
    - It suggests a growing **data-driven culture**, where visualization and analysis are integral to SCM strategy.
- **Sales & Operations Planning (S&OP)** and **Master Production Scheduling (MPS):** These strategic planning areas show moderate adoption:
    - **S&OP: 13 mentions**, with Cloud and AI most represented.
    - **MPS: 16 mentions**, led by Cloud and AI again.
    - These levels suggest that **advanced planning capabilities are starting to be enhanced**, but to a lesser extent than execution.

- **Forecasting & Inventory Optimization:** With only **17 mentions**, this area sees relatively **lower technological involvement**, despite its criticality.
    - AI and Cloud lead here, as expected, but limited use may reflect challenges in data quality or system integration.
    - This points to **a gap between perceived importance and actual deployment** in predictive logistics and planning.

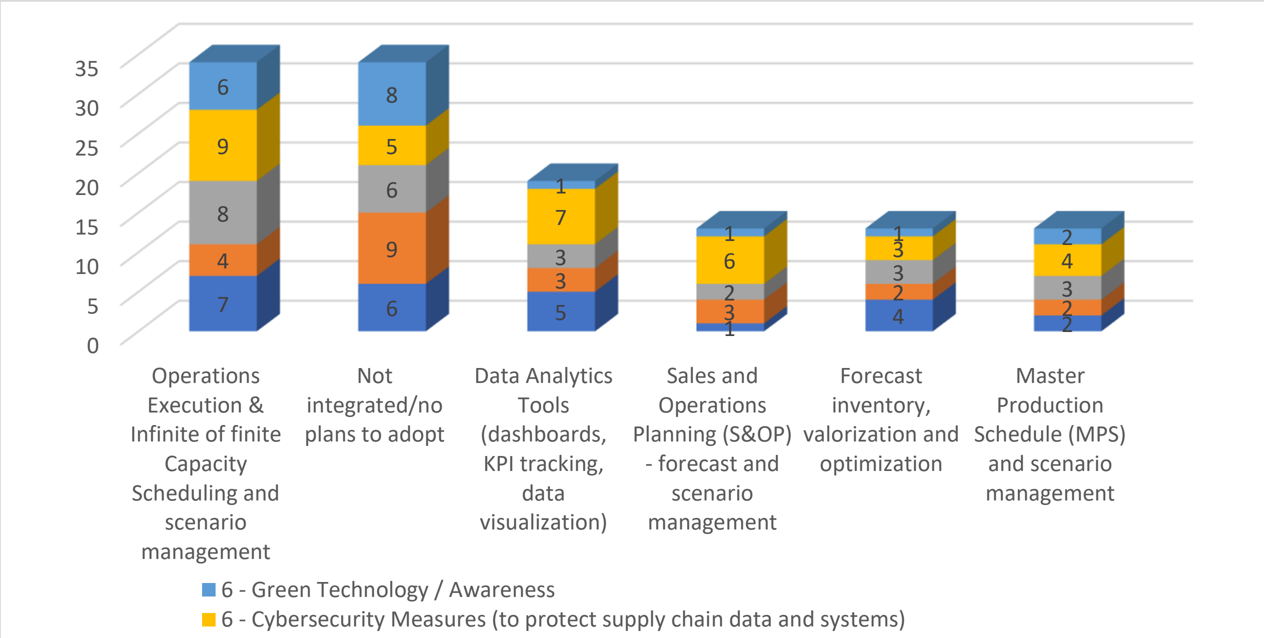

Figure 16. Current use or planned adoption of emerging technologies in SCM 4.0

Focusing on small and medium-sized enterprises - which represent the majority of respondents in this survey - we can identify their current use or planned adoption of Industry 4.0 technologies within their Supply Chain Management processes:

- **Medium Enterprises (50–249 employees):** Most advanced and diversified adopters of emerging technologies across nearly all SCM process levels.
    - Strongest uptake is seen in operations execution, planning, and cybersecurity, with consistent use of IoT, AI, and Cloud.
    - Despite this, some resistance or lack of maturity persists (notably 4 “not integrated” for AI and Green Tech), indicating room for targeted support in these areas.

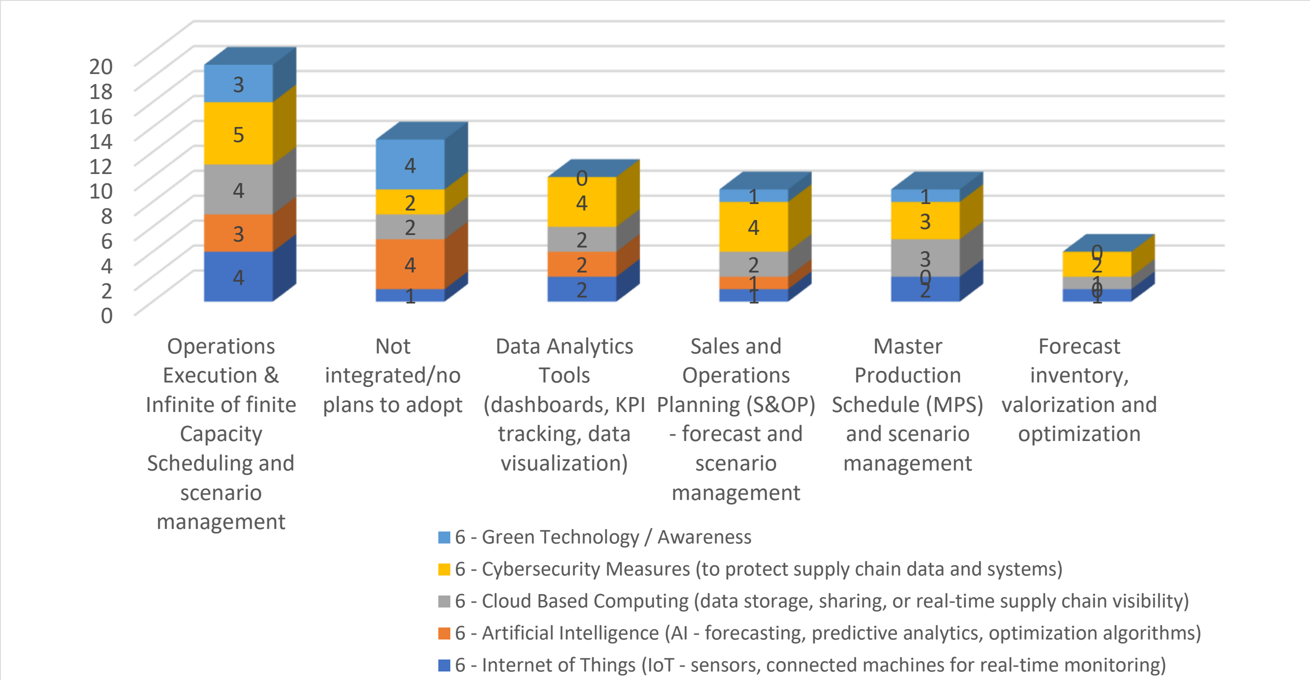

Figure 17. Current use or planned adoption of emerging technologies in SCM 4.0 – Medium Enterprises

- **Small Enterprises (10–49 employees):** Adoption is **more selective and uneven**, with the majority of technologies still not integrated in many SCM functions.
  - Some progress is observed in **operations execution**, **data analytics** and **forecasting**, but planning levels (S&OP, MPS) remain under-addressed.
  - Cybersecurity sees relatively better integration here than expected, pointing to **growing awareness of risks** even in smaller structures.

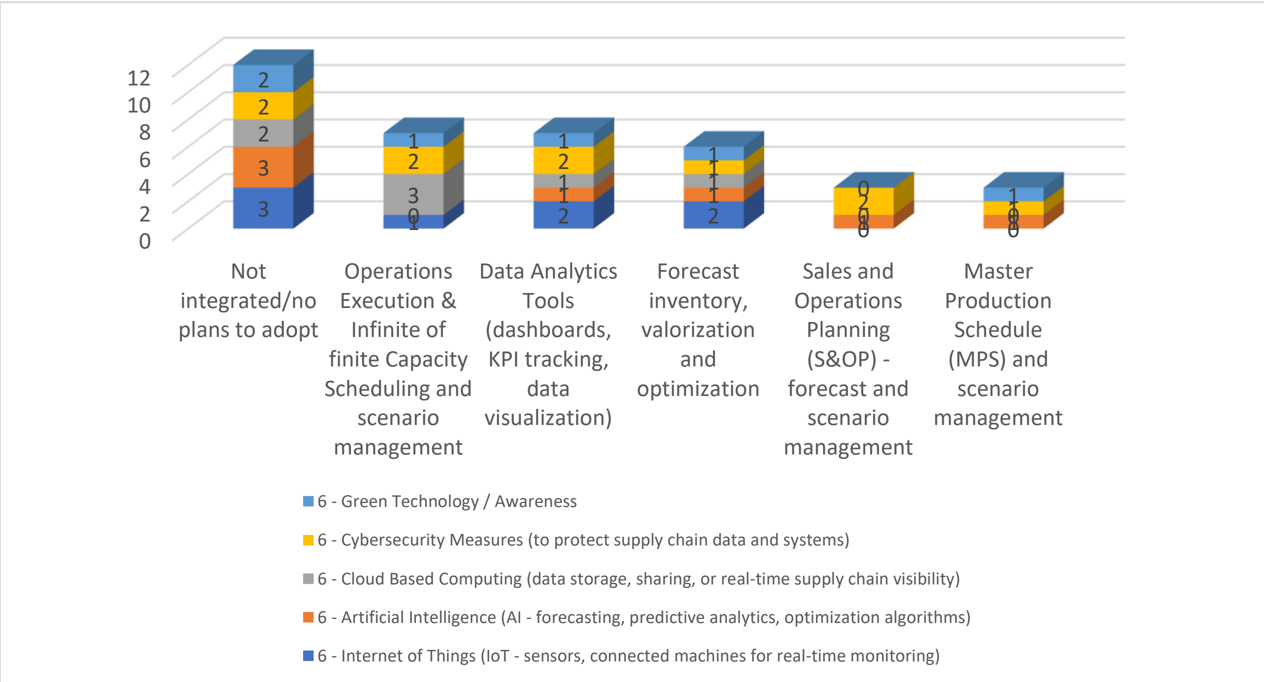

Figure 18. Current use or planned adoption of emerging technologies in SCM 4.0 - Small Enterprises

Conclusion

The analysis reveals that ***Operations Execution & Scheduling*** is the most advanced area in terms of Industry 4.0 technology adoption, reflecting a strong focus on shop-floor efficiency, flexibility, and responsiveness, particularly through IoT, AI, and Cloud solutions. ***Data analytics*** also shows high adoption, indicating a shift toward performance-driven supply chain strategies. In contrast, strategic planning areas such as ***S&OP*** and ***MPS*** exhibit only moderate uptake, and ***forecasting*** remains under-leveraged despite its importance. A notable share of companies - particularly small enterprises - report no current or planned integration of key technologies, highlighting barriers such as complexity, cost, or lack of perceived ROI. Medium-sized enterprises appear as the most mature adopters, though still facing adoption gaps in areas like AI and sustainability.

These results suggest that while operational digitalization is underway, broader strategic integration and targeted support are needed, especially for smaller firms.
The high number of companies with **no adoption plans -** especially for transformative technologies like AI and IoT - highlights a **need for awareness, capacity-building, and support** to accelerate adoption across the entire supply chain.

6.4.7. MAIN OBSTACLES TO THE ADOPTION OF EMERGING TECHNOLOGIES IN SCM 4.0

The chart on **Main Obstacles to the Adoption of Emerging Technologies in SCM 4.0** highlights clear trends in the barriers perceived by companies of different sizes:

- **Technological Complexity & Integration** is by far the most cited obstacle (44% of overall respondents), affecting **all company sizes**, but especially **medium-sized enterprises (42% mentions)** and **small businesses (52% mentions)**. This suggests that even though these companies may be open to adopting technologies, they often face challenges with system interoperability, legacy infrastructure, or technical implementation know-how.
- **Organisational & Cultural Resistance** ranks second (31% of overall respondents), particularly among **micro (57% mentions)** and **medium-sized enterprises (32% mentions)**. This underscores internal hesitation, perhaps due to change management issues, lack of staff engagement, or limited digital culture in these environments.
- **Financial & Strategic Constraints** (17% of overall respondents) are also a notable barrier, especially for **large (22% mentions)** and **small (19% mentions)** companies. This reflects limited budgets or uncertainty in returns on investment, which can delay or block technology-related decisions.
- **Security, Privacy & Ethical Concerns** appear less prominent (8% of overall respondents), mostly affecting **medium and large enterprises (11% mentions for both)**. These concerns may grow in importance as adoption progresses, particularly with AI, IoT, and cloud-based tools handling sensitive data.

In summary, the biggest hurdle is clearly the **technological and integration complexity**, followed by internal resistance to change. Financial constraints and data security appear as secondary but still relevant factors. These insights highlight the need for simplified, interoperable solutions, change management support, and clearer ROI paths—especially for SMEs navigating digital transformation.

(To enhance readability and account for variations in sample sizes across company categories, the percentages represent the relative proportion within each company size group.)

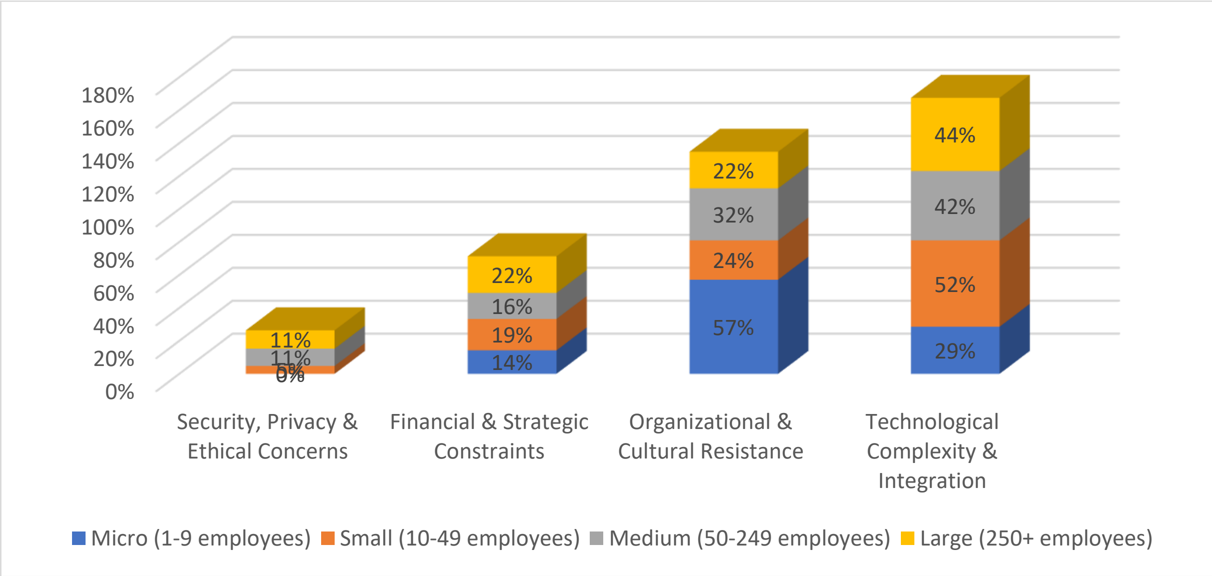

Figure 19. Main obstacles to the adoption of emerging technologies in SCM 4.0

6.4.8. EXTERNAL FACTORS INFLUENCING EMERGING TECHNOLOGIES 4.0 ADOPTION

For Small companies (10-49 employees) **Technological readiness** and **Customer demand** (22% each of their answers in the segment) emerge as the most frequently cited motivators, while for Medium companies (50-249 employees) **Market pressure** and **Technological readiness** (respectively 25 and 20% each of their answers in the segment) emerge as the most frequently cited motivators, indicating that these companies tend to adopt innovations when they see both a clear need from their customers and internal confidence in their capabilities.

Government incentives (mentioned by 11% of small companies and 15% of medium companies) also play a substantial role, reflecting the influence of broader economic and regulatory environments.

A notable number of respondents (13% of all mentions) also selected "**Not applicable/Not familiar**" signaling that for some, the relevance or awareness of these external drivers remains limited (a potential area for support and awareness raising initiatives?).

6.4.9. CURRENT SKILLS GAPS IN WORKFORCE RELATED TO EMERGING TECHNOLOGIES 4.0

For **large companies (250+ employees)**, the most prominent skill gaps are found in **cloud-based computing expertise** and **AI tool usage**, indicating that even well-resourced organisations face internal capability constraints when integrating advanced technologies. This suggests that the speed of technological change may be outpacing internal upskilling efforts, even in mature structures. **(reminding that the sample of this segment is not really reliable).**

In **medium-sized companies (50–249 employees)**, there is a strong emphasis on **AI tool usage**, **IoT management**, and **data analysis**, all receiving significant relative attention. This reflects a clear ambition toward digital transformation but also highlights that the workforce is struggling to keep pace with required competencies in these key domains.

Small companies (10–49 employees) most frequently cite **IoT management**, followed by **AI tool usage**, suggesting a growing demand for operational tech adoption—yet an evident lack of technical readiness. The lower reporting of data analysis gaps could indicate either less data-centric operations or a lower awareness of the strategic value of such skills.

Micro enterprises (1–9 employees) show a more fragmented picture, with **AI tool usage** and **data analysis** emerging as the main challenges, though the overall number of responses is lower. This suggests limited engagement or awareness in some areas, possibly due to resource constraints or the early stage of digital maturity.

Overall, this chart confirms that **AI and IoT-related skills gaps are widespread across all segments**, while **cloud expertise** is a particular concern in larger firms. The consistent presence of these gaps across different company sizes underlines the need for **tailored training strategies**, aligned with each organisation's scale and technological roadmap.

Not applicable / Unfamiliar" is underlined by 14% of all mentions, **particularly** among small and medium-sized enterprises. This points to a persisting lack of awareness or understanding of certain emerging technologies, which could hinder informed decision-making and slow adoption.

(To enhance readability and account for variations in sample sizes across company categories, the percentages represent the relative proportion within each company size group.)

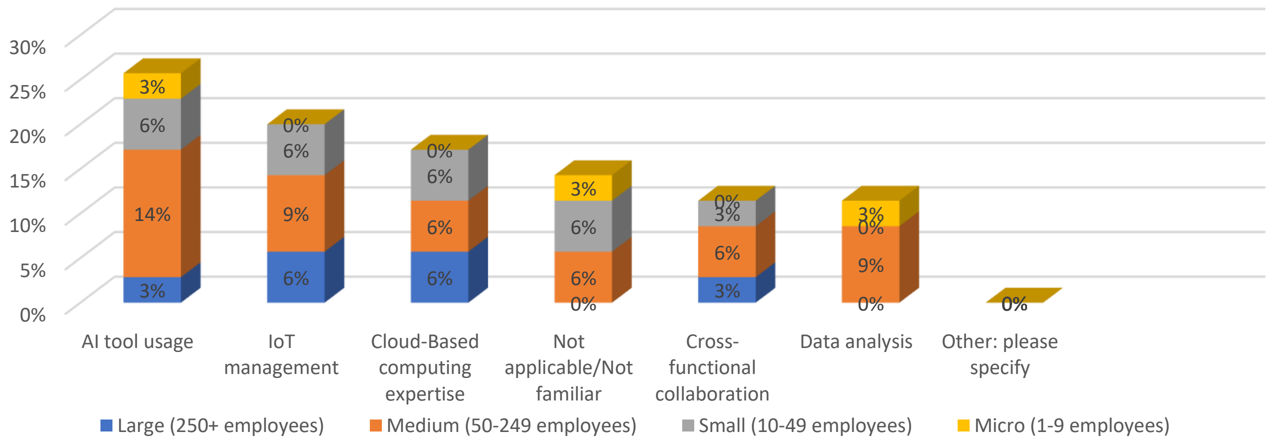

Figure 20. Current skills gaps in workforce related to emerging technologies 4.0

6.4.10. PLANNED TRAINING ON EMERGING TECHNOLOGIES 4.0

The chart indicates that training efforts related to emerging technologies 4.0 target decision-makers significantly. However, a significant portion of respondents either have no training plans or schedule them beyond five years, suggesting a lack of awareness or prioritization. Additionally, no specific technology emerges as a clear focus, reflecting uncertainty or limited visibility regarding the key digital skills to develop for future supply chain transformation.

(To enhance readability and account for variations in sample sizes across company categories, the percentages represent the relative proportion within each company size group.)

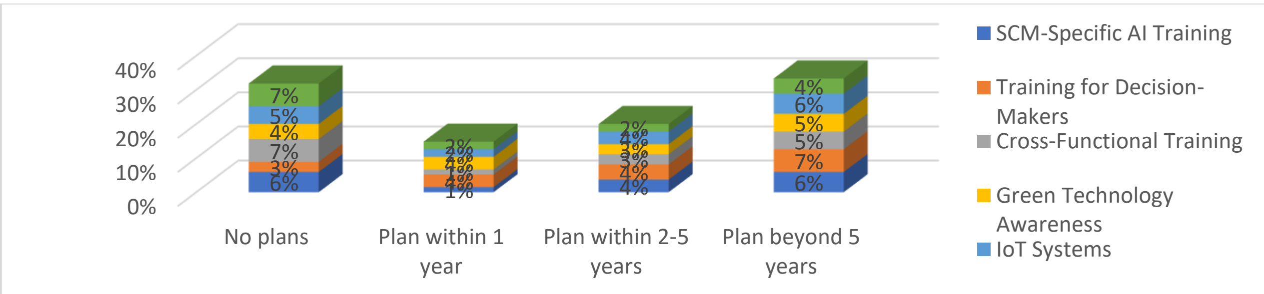

Figure 21. Planned training on emerging technologies 4.0 for SCM

Apart from large companies (though the sample is not statistically significant) and small companies that indicate plans for training within the coming year, the survey results predominantly reflect training actions that are either **not planned at all** or scheduled **beyond the next two years**. This points to a widespread delay in addressing upskilling needs related to emerging technologies in SCM.

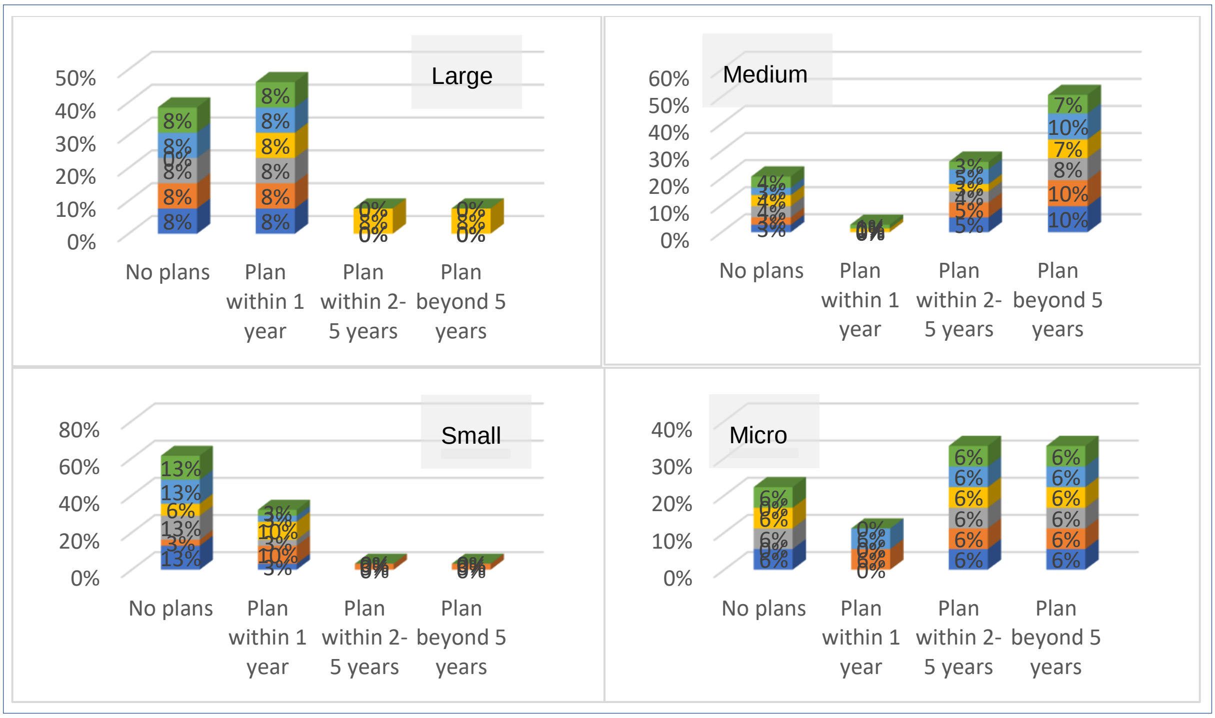

Figure 22. Planned training on emerging technologies 4.0 for SCM per company size

6.4.11. TYPE OF TRAINING WHICH CAN IMPROVE SCM PROCESSES

Training needs are reported across both decision-makers and technicians (EQF 4 to 6), reflecting the importance of upskilling at all organisational levels.

However, most training mentions concern **managers/decision-makers**, suggesting that strategic leadership is seen as essential in SCM's digital transformation. This may also reflect the respondent profiles.

In terms of content, **no single training type dominates**, showing that companies recognise the need for **diverse skills**, from AI and IoT to green tech and cloud. **"Training for Decision-Makers"** and **"Cross-Functional Training"** are frequently cited, indicating a growing focus on **breaking silos and building transversal capabilities**.

The significant share of "Not applicable / Not familiar" answers suggests that many companies lack clarity on training options or needs, confirming a broader trend of limited or long-term planning for training actions.

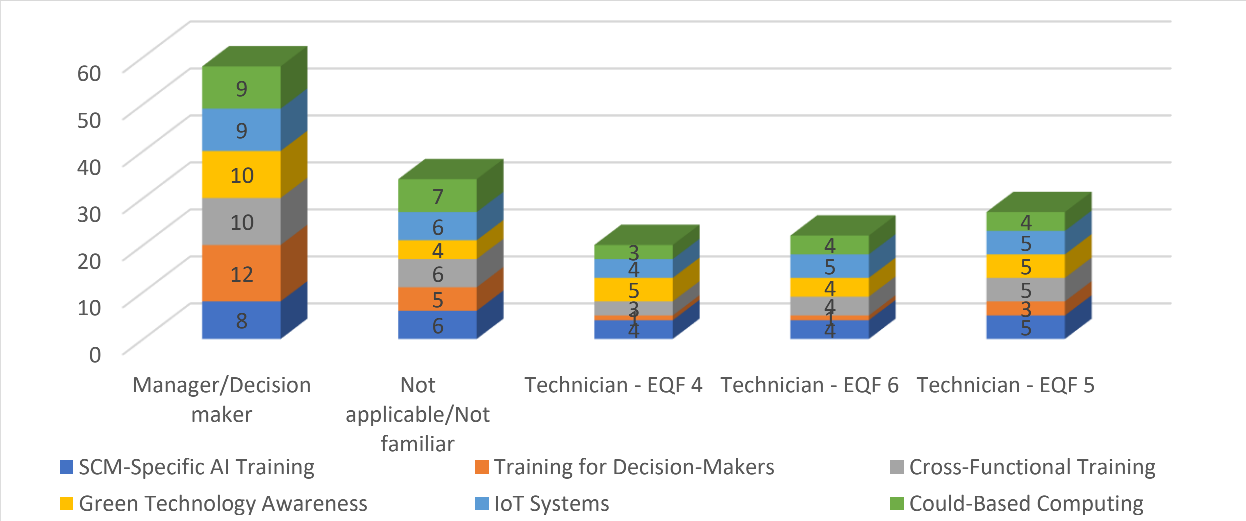

Figure 23. Type of training which could be most beneficial to improve SCM processes

6.4.12. PLANNED LEVEL OF INVESTMENT IN AI IN THE NEXT 3 YEARS

(To enhance readability and account for variations in sample sizes across company categories, the percentages represent the relative proportion within each company size group.)

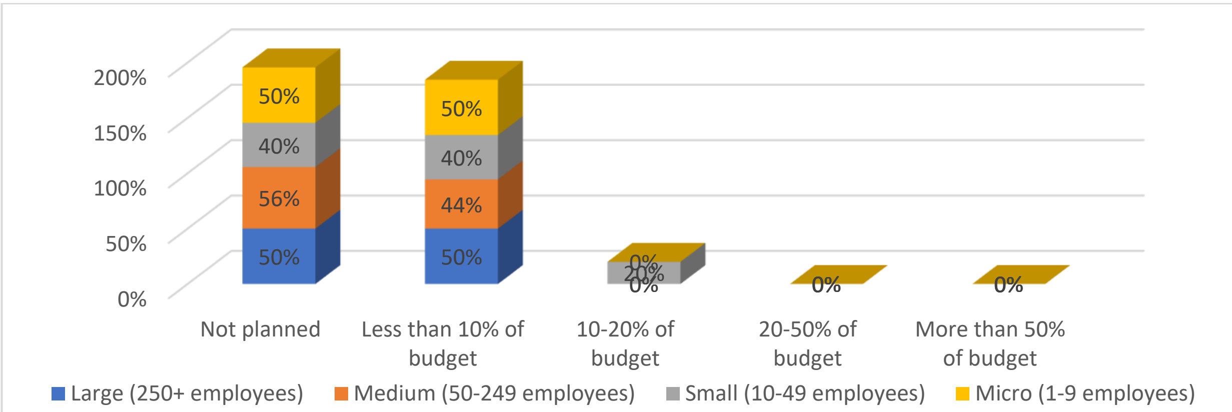

Figure 24. Planned level of investment in AI in SCM in the next 3 years

The chart reveals a very low level of planned investment in AI across all company sizes over the next three years. Except only **one small company** which reported a future investment in the **10–20% range,** 100% of other respondents indicate that AI investments are either not planned at all or will represent less than 10% of their overall budget.

This distribution clearly suggests that while awareness of AI is growing, its prioritization in terms of budget allocation remains limited, likely due to perceived barriers such as cost, complexity, or lack of internal readiness. The data also reflects cautious or exploratory attitudes toward AI adoption, with larger investments still far from the norm, especially among micro and small companies.

6.4.13. TYPES OF TRAINING TO SUPPORT WORKFORCE FOR SCM

The chart shows that **in-person training** (whether internal or external) is the **most commonly preferred format** overall, especially among **micro-enterprises**, where 67% of mentions fall in this category. It is also well represented among **medium and small companies**, indicating a general preference for traditional, direct learning environments.

Hybrid training models - which combine online and in-person formats - are **particularly favored by large companies** (67%), indicating an interest in flexibility and adaptability in workforce upskilling. Smaller companies are less represented here, perhaps due to limited infrastructure or experience with blended learning.

Online training comes next, with support across all company sizes, especially among **large enterprises** (33%), suggesting openness to digital formats, likely due to scalability and accessibility.

Flexible scheduling appears as a secondary preference for **medium companies**, while **custom or other formats** are rarely cited, implying a limited interest or perhaps lack of clarity in what those options would entail.

In summary, while preferences vary slightly by company size, structured and synchronous training (online or in-person) dominates, and larger firms tend to favor more adaptable hybrid models, whereas micro and small companies still lean toward in-person formats.

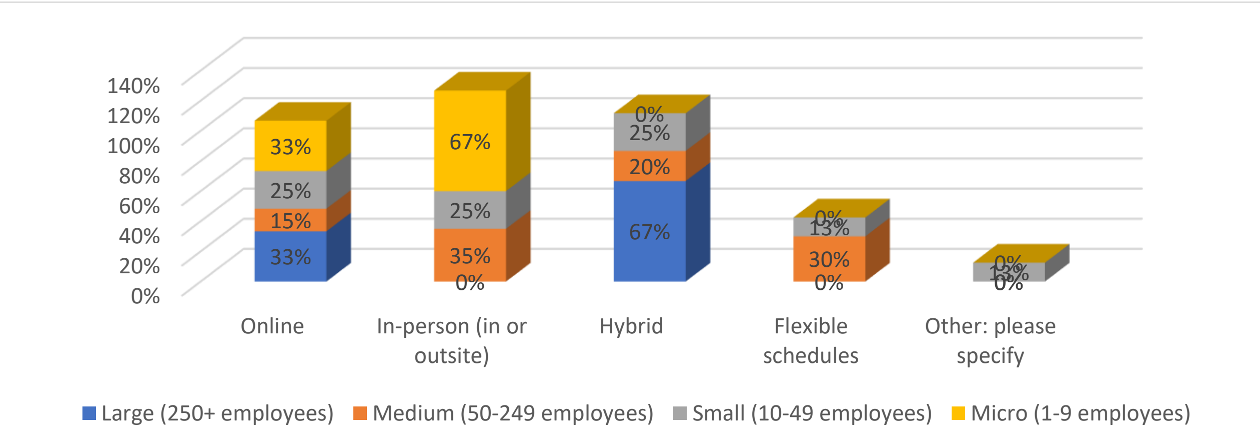

Figure 25. Types of training to support workforce for SCM

6.5. FUTURES PERSPECTIVES & RECOMMANDATIONS

The adoption of SCM 4.0 technologies is a strategic lever for transforming small and medium-sized enterprises (SMEs) in Europe. However, the LCAMP survey results highlight that this transition remains partial, unevenly distributed across countries and sectors, and often limited to pilot initiatives.

SMEs face several challenges in adopting digital supply chain solutions:

- **Strong financial constraints** that limit access to advanced technologies such as AI, digital twins, or predictive analytics.
- **Lack of internal expertise** to drive digital transformation in supply chain processes.
- **Limited awareness of the added value** these technologies can bring to short or semi-automated production cycles.
- **Insufficient integration of sustainability goals**, such as Scope 3 emissions monitoring and circular supply chain models.

At the same time, SMEs that have begun implementing SCM 4.0 tools report tangible benefits: improved planning accuracy, better anticipation of supply disruptions, enhanced responsiveness, reduced logistics costs, and increased traceability.

6.5.1. BUILDING TRUST, TRANSPARENCY, AND INFORMATION SHARING IN SUPPLY CHAINS

The evolution of business-to-business relations between customers and suppliers is increasingly marked by digital technologies. However, while digital tools offer unprecedented transparency and efficiency, the human dimension of trust, already mentioned more than twenty years ago in these two reports (T. Y. Choi et al., 2001; Dyer & Chu, 2003), remains fundamental to lasting collaboration (David LaBar, 2019; Faruquee et al., 2021; Maria Jesús Saénz et al., 2022; Patrick Huser, 2023)

1. **Digitalization as a trust enabler**

The digitalization of procurement processes - such as through Supplier Relationship Management (SRM) platforms - provides real-time visibility into operations. This improved transparency strengthens mutual understanding and facilitates faster, more accurate exchanges. Digital tools thus act as catalysts for building long-term trust between buyers and suppliers.

2. **Alignment with customer expectations: the foundation of loyalty**

According to Accenture, 80% of B2B buyers have switched suppliers within two years due to misalignment with their expectations. Digital innovation alone is not enough; trust is earned when suppliers combine technological efficiency with personalized human interaction. Organisations that can harmonize digital solutions and relational engagement secure stronger customer loyalty, improve profitability, and increase market share.

3. **The need for balanced management**

Managing B2B relationships today requires a careful balance: leveraging the advantages of digitalization (automation, data sharing, collaborative tools) without neglecting relational elements such as transparency in decision-making, active listening, and proactive communication.

4. **Trust and quality of information: twin pillars of performance**

The relevance, reliability, and openness of shared information - enabled by both technology and human processes - are crucial to empower decision-making and avoid the inefficiencies of fragmented or mistrustful supply chains.

6.5.2. STRATEGIC RECOMMENDATIONS

The evolution toward Supply Chain 4.0 requires coordinated actions across multiple dimensions: digitalization, human capital development, innovation, sustainability, and trust management. Based on recent insights, the following strategic actions are proposed (David LaBar, 2019; Faruquee et al., 2021; Maria Jesús Saénz et al., 2022; Patrick Huser, 2023).

1. **Digitise Procurement and Supplier Relationship Management**
   - Implement advanced Supplier Relationship Management (SRM) systems and collaborative digital platforms to enable real-time data exchange, operational visibility, and improved coordination.
   - Promote the use of low-code/no-code platforms for easier data management and process automation, especially for SMEs.
   - Encourage modular and subscription-based models, such as Equipment-as-a-Service (EaaS), to lower barriers to entry for smaller businesses.
2. **Leverage Digital Tools to Foster Transparency**
   - Use technology not only for automation but to create open, traceable communication across procurement processes, contracts, and supplier performance monitoring.
   - Develop regional demonstrators and living labs for SCM 4.0 to showcase transparent, collaborative models, in collaboration with industrial clusters and Centres of Vocational Excellence (CoVEs).
3. **Strengthen Data Governance and Information Security**
   - Develop robust policies and infrastructures to ensure secure, confidential, and compliant information-sharing practices across the supply chain.
4. **Align Supplier Services with Customer Expectations**
   - Establish continuous feedback mechanisms to adapt supplier offerings to evolving customer needs, avoiding standardized approaches that ignore individual client profiles.
5. **Balance Digital Efficiency with Human Engagement**
   - Combine technological efficiency with personalised relationship management to maintain emotional commitment, loyalty, and trust within supplier networks.
6. **Promote a Collaborative Partnership Culture**
   - Foster a shift from transactional relationships to genuine partnerships based on mutual respect, shared goals, transparency, and co-innovation.
   - Stimulate joint SME innovation projects focused on shared logistics, digital traceability, or data interoperability.
7. **Invest in Workforce Upskilling and Relational Capabilities**
   - Strengthen cooperation with VET providers to offer short, targeted programs in digital logistics, data analysis, and automated planning.
   - Support continuous learning among SME staff through hybrid formats (in-person, online, and simulation-based training).

- Train employees in relational skills such as trust-building, negotiation, and collaborative decision-making.

8. **Strengthen Change Management Support**

- Facilitate organisational cultural shifts toward openness, collaboration, and digital adoption.
- Offer tailored "Supply Chain 4.0" diagnostics at regional or sectoral levels to guide SMEs through their digital transformation journeys.
- Develop co-financed advisory services to help SMEs implement digital strategies, leveraging regional and EU funding opportunities.

9. **Embed Digital Transformation Within Green Transition Strategies**

- Raise awareness among SME managers about the importance of Scope 3 emissions, sustainable logistics, and circular economy models.
- Support the integration of environmental KPIs into digital supply chain strategies to align digitalization with climate and sustainability goals.

10. **Conduct Regular Trust and Relationship Audits**

- Periodically evaluate the quality of trust, communication, and collaboration within supplier networks to identify risks early and drive continuous improvement.

6.5.3. THE NEED FOR COORDINATION

The successful transformation of SMEs requires better alignment between enterprise support schemes, VET systems, and regional Smart Specialisation Strategies (S3). The intersection of technological innovation, skills development, and sustainability should form the backbone of regional industrial policies and roadmaps.

In the **policy paper** (OECD, 2021) describe Governments and ecosystems recommend to:

- Improve **access to AI-related training and awareness** programs.
- Support **data-sharing frameworks** and accessible AI platforms.
- Create **testbeds and pilots** to help SMEs explore AI use cases with low risk.

6.6. CONCLUSION

The digital and green transitions are redefining the operational and strategic environment for SMEs across Europe. While SCM 4.0 offers significant potential for performance gains, resilience, and sustainability, the transition remains challenging - especially for smaller firms with limited resources.

The main conclusions of the literature review, confirmed by the results of the survey carried out in France, Germany, Italy, Slovenia and Turkey, are a **low to moderate level of adoption** of SCM 4.0 tools and technologies. Most companies acknowledge the **relevance of digital solutions**, particularly in planning and forecasting, yet cite **barriers such as high costs, lack of expertise, and unclear return on investment** as major inhibitors. Few SMEs currently integrate advanced technologies such as AI, IoT, or blockchain into their supply chain processes, and many remain unaware of the benefits or implementation pathways.

Moreover, sustainability considerations are gaining ground, but often remain **under-prioritised or disconnected** from digitalisation efforts. Many SMEs are still unfamiliar with the concepts of circular logistics or Scope 3 emissions, highlighting a need for **targeted awareness campaigns and support tools**.

The findings also reveal **uneven preparedness of the workforce**, with skill gaps identified in both technical domains (data analytics, digital planning tools) and soft competencies (change management, sustainability literacy). This further reinforces the importance of closer collaboration between SMEs and vocational training institutions to co-develop agile, responsive learning pathways.

In addition, the shift toward digitalized supply chains must not overlook the human dimension that underpins effective collaboration. Trust, transparency, and relational excellence between customers and suppliers are critical enablers of successful digital transformation. Strengthening open communication channels, aligning expectations, and balancing digital efficiency with human engagement will be essential to building resilient, future-ready B2B ecosystems.

In conclusion, unlocking the full potential of SCM 4.0 in SMEs will require a **coordinated effort combining financial support, tailored training, technology accessibility, and regional innovation ecosystems**. Strategic guidance, simplified access to scalable tools, and hands-on experimentation will be key to empowering SMEs to embrace digital and sustainable supply chain management.

7. IMPACT OF SCM 4.0 ON TRAINING AND TRAINING CENTRES

The rise of emerging Industry 4.0 technologies —such as artificial intelligence (AI), big data, autonomous robotics, cloud computing, machine learning, digital twins, blockchain, the Internet of Things (IoT), cybersecurity, augmented reality (AR), and virtual reality (VR), among others— is redefining supply chain standards across Europe. These innovations are revolutionizing both job roles and training programs, which have already begun to incorporate, to varying degrees, content related to these technologies in response to labor market demands.

In countries such as France, Germany, Slovenia, Turkey, Sweden, and Italy, there are training programs specifically dedicated to supply chain management (SCM) or related areas, aimed at preparing professionals who can effectively integrate into SCM teams.

This chapter will analyse the impact of emerging technologies on training centres and their academic programs. While a wide range of SCM-related training is available at Levels 7 and 8 of the European Qualifications Framework (EQF)—that is, master's and doctoral levels—this chapter will focus on programs at Levels 4 to 6, corresponding to upper secondary education (BAC) up to the equivalent of a bachelor's degree.

First, we will present examples of existing training programs in SCM and related fields. Next, we will explore the impact of new technological trends on training centres, highlighting both challenges and opportunities. Finally, we will examine how these changes are being reflected in curriculum content, in-demand skills, and the adoption of new pedagogical strategies.

7.1. SCM TRAINING PROGRAMS AND RELATED PROFESSIONS

Below are some examples of specialized training programs in Supply Chain, as well as other related professional training programs. These programs have already started integrating emerging approaches and technologies.

In France, some prominent training programs in supply chain management (SCM) include the **Bachelor's Degree in Technology: Logistics and Transport Management, Sustainable Mobility and Supply Chain Specialization**, which integrates innovative technologies and digital solutions applied to logistics and transport. Another notable program is the **Professional Bachelor's Degree in Logistics and Flow Management**, which covers warehouse automation, cybersecurity, and sustainable management ('RNCP35390 - BUT - Management de la logistique et des transports', n.d.; 'RNCP40064 - Licence Professionnelle - Logistique et pilotage des flux (fiche nationale)', n.d.-a).

In Germany, the **Certified SAP User in Production Planning** course focuses on production planning using the SAP system, covering master data management, production orders, and inventory movements. Meanwhile, the **Strategic Supply Chain Management** program addresses the strategic planning and management of logistics networks through simulations and cost optimization strategies (Haufe Akademie GmbH & Co. KG, n.d.-a; *Weiterbildung SAP Produktionsplanung -und steuerung (PP)*, n.d.).

In Italy, the **Supply Chain, Logistics and Operations** course focuses on inventory management, ERP use, Blockchain, RFID, IoT, automation, robotics, and data analysis (*Master Supply Chain, logistica e operations Professional*, n.d.).

In Turkey, the **Bachelor's Degree in Logistics** offers training in supply chain management, inventory control, and logistics information systems. Additionally, the **Associate Degree in Logistics** is oriented towards storage, transportation, and inventory management (Ãœniversitesi, n.d.).

7.2. CHALLENGES AND OPPORTUNITIES FOR TRAINING CENTRES

Digitalization is profoundly transforming the supply chain by automating many tasks and creating new jobs. Traditional roles, such as those of buyer, logistics manager, or production manager, are evolving to become more strategic, thanks to the integration of data analysis and automation. New professions are emerging, such as data scientist, robotics expert, augmented reality specialist, and blockchain manager. These professionals provide innovative solutions to optimize flow management, improve maintenance, and enhance transaction security.

(Blanco, 2022; Iynkus, n.d.; Movant, 2024).

7.2.1. THE EVOLUTION OF TRAINING PROGRAMS

Training centres must adapt to economic and technological changes by integrating major trends and aligning the targeted skills. Digital transformation has enabled greater flexibility and accessibility in training pathways, with the rise of hybrid models combining online and in-person learning. This model not only facilitates the transmission of technical skills but also promotes networking and professional integration.

7.2.2. GROWING DEMAND

Training institutions are facing a growing demand for specialized learning, accompanied by an increase in the number of students. This trend represents a major opportunity for the diversification and modernization of training offerings.

However, these transformations also come with challenges:

- Maintaining the balance between traditional training and new immersive technologies, such as the metaverse.
- Adapting educational content to the changing needs of the market and the new expectations of businesses.
- Encouraging continuous learning to enable professionals to quickly adapt to innovations.

In Spain, a Master's program in Supply Chain Management was created in 2024 to respond to the growing demand for professionals in the field. This Master's program was developed by the Business School of the Madrid Chamber of Commerce, Industry, and Services in collaboration with the Complutense University of Madrid. Although Master's level education is not the focus of this report, it serves as an example of the aforementioned growing demand (Redacción, 2024).

7.2.3. CHALLENGES IN TECHNOLOGICAL INVESTMENT FOR TRAINING CENTRES

One of the main challenges for supply chain training centres is the need to invest in new technologies and advanced equipment. However, many centres lack the autonomy to make quick decisions regarding technological investments, or they do not always have the necessary financial resources to implement these improvements. This limits their ability to offer innovative training.

7.2.4. TRAINING OF TRAINERS

According to the report *"Tensions on Workforce and Skills in Industry and Associated Training Schemes"* (Federico Berera et al., 2022), like other European countries, is facing a shortage of qualified trainers in many industrial sectors. The report highlights that a large proportion of current trainers are not sufficiently prepared to teach emerging technologies such as Artificial Intelligence, the Internet of Things (IoT), and robotics.

60% of trainers in the industrial sector are not trained in the new digital technologies required for Industry 4.0.

A shortage of skills in the digital and ecological fields has been identified, leading to inefficiencies in the transmission of knowledge in key areas such as Supply Chain Management (SCM) and sustainable production.

The report emphasizes that current training systems are not adequate to address this gap. It is therefore necessary to adopt continuous professional development programs for trainers, including specialized modules in emerging technologies and sustainable supply chain management.

7.2.5. ALLIANCES WITH THE INDUSTRIAL SECTOR: AN OPPORTUNITY FOR TRAINING CENTRES

Alliances with the industrial sector, facilitated by new technologies, represent a great opportunity for supply chain training centres. These collaborations allow for practical and up-to-date training. Many centres already have partner networks that directly connect them to the industry, enabling them to quickly adapt to technological advancements and respond to market demands.

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7.3. EMERGING TECHNOLOGIES AND FIELDS INTEGRATED INTO TRAINING PROGRAMS RELATED TO SCM

7.3.1. FOCUS ON SUSTAINABILITY AND ENVIRONMENTAL RESPONSIBILITY

Many training programs already integrate a sustainability and environmental responsibility approach. One example is the **Bachelor of Technology Management in Logistics and Transport: Mobility and Sustainable Supply Chain**, which trains professionals to manage the logistics and transport chain with a focus on sustainability. The skills acquired include resource optimization, the implementation of sustainable development strategies, and the integration of responsible practices in logistics and mobility.

Graduates learn to conduct sustainable logistics audits, develop innovative solutions with environmental criteria, and apply Corporate Social Responsibility (CSR) strategies in the logistics field. Additionally, they are trained to manage public and private transport with a sustainable mobility approach, ensuring energy efficiency and minimizing environmental impact ('RNCP35391 - BUT - Management de la logistique et des transports', n.d.).

Another example of specialized training in sustainability is found in Germany: the **Sustainability in Supply Chain Management** seminar. This program provides key knowledge for achieving socially, ecologically, and economically sustainable supply and production chains. It addresses regulations such as the Supply Chain Due Diligence Act and upcoming EU directives, offering solutions to measure and optimize sustainability.

Participants learn to integrate sustainability into strategic planning and operational management, addressing the balance between economy, ecology, and social aspects. The seminar also explores the role of supply chain management in promoting sustainability, methods to enhance competitiveness, and exemplary practices.

At the end of the seminar, participants gain a clear understanding of the legal framework and strategies to achieve long-term sustainability in the supply chain (Haufe Akademie GmbH & Co. KG, n.d.-b).

7.3.2. CYBERSECURITY INTEGRATED INTO TRAINING PROGRAMS

Just as many training programs integrate sustainability and environmental responsibility, many also adopt a strong focus on cybersecurity. These programs address the challenges related to IT security and the protection of systems (security of goods and individuals). The programs emphasize the use of digital tools and the application of cybersecurity rules to acquire, process, produce, and disseminate information, as well as to collaborate both internally and externally.

Some training programs specifically focus on implementing security policies for the protection of data stored in a cloud infrastructure, incorporating preventive measures against intrusions, fraud, data breaches, or leaks through the configuration of the information system. Among these programs are, notably, Quality, Industrial Logistics, and Organisation, specializing in Organisation and Supply Chain (EQF 6), Logistics and Transportation Management, specializing in Mobility and Sustainable Supply Chains (EQF 6), as well as the Professional Bachelor's degree in Logistics and Flow Management (EQF 6) ('RNCP35351 - BUT - Qualité, Logistique Industrielle et Organisation', n.d.; 'RNCP35391 - BUT - Management de la logistique et des transports', n.d.; 'RNCP40064 - Licence Professionnelle - Logistique et pilotage des flux (fiche nationale)', n.d.-b).

There are also specialized training programs in cybersecurity, such as the IT Infrastructure and Security Technician (EQF 5). This technician ensures the proper functioning of the company's computer networks and telecommunications, usually under the responsibility of a network engineer, by guaranteeing their availability and security while participating in their evolution in compliance with guidelines and service contracts. Their scope of intervention may extend on-site, remotely, and in the Cloud. They contribute to the maintenance and supervision of IT equipment and software to ensure service continuity and manage the inventory of IT hardware (‘RNCP39620 - Technicien d’infrastructure informatique et sécurité’, n.d.).

In summary, the competencies identified in training programs within the Supply Chain area can be summarized as follows:

- **Logistics data protection:** Ensuring the security of information generated in transportation and storage operations.
- **Cloud infrastructure security:** Implementing protection measures in platforms used for inventory and flow management.
- **Application of cybersecurity strategies:** Ensuring the safe use of digital tools and interconnected systems within the supply chain.

Mitigation of cyber risks: Preventing and managing threats such as cyberattacks, data leaks, and failures in technological infrastructure.

7.3.3. IA INTEGRATED INTO TRAINING PROGRAMS

Several training programs now include skills in artificial intelligence (AI) in their curricula. Among them is the Bachelor's degree in Science and Engineering, specializing in Maintenance of Intelligent and Connected Systems (EQF 6), which incorporates new technologies as well as the exploitation and analysis of data and indicators. This program implements artificial intelligence techniques to optimize predictive maintenance, robotics, mechatronics, and computer-aided maintenance management (CMMS) (‘RNCP38710 - Grade_Licence - Sciences et Ingénierie - Maintenance des Systèmes Intelligents et Connectés’, n.d.).

Similarly, the Bachelor's degree in Science and Engineering - Information Systems (EQF 6) trains professionals capable of processing and analysing data to extract strategic information and communicate it to their colleagues to facilitate decision-making. Using digital tools and advanced algorithms, including artificial intelligence models, this program develops skills in data processing and synthesis, essential for advanced analysis and the effective use of information (‘RNCP39709 - Grade_Licence - Sciences et Ingénierie - Systèmes d'information’, n.d.).

Other training programs, such as the Bachelor's degree in Science and Engineering - Computer Science and Digital Systems (EQF 6), focus on more specialized skills, including the development and management of databases, the integration of AI into application development, and the design and optimization of artificial intelligence solutions for industry. These programs also train students in the organisation and management of AI projects, incorporating an ethical and ecological approach to support the digital transformation of businesses (‘RNCP38732 - Grade_Licence - Sciences et ingénierie - Informatique et Systèmes Numériques’, n.d.).

Moreover, the IT Project Coordinator (cloud infrastructures, applications, or data) (EQF 6) also includes teachings related to the development of artificial intelligence tools, while the Data Science Developer focuses on predictive data analysis using artificial intelligence (‘RNCP35288 - Concepteur développeur en science des données’, n.d.; ‘RNCP38478 - Coordinateur de projets informatiques (infrastructures cloud, applicatives ou data)’, n.d.-a).

The "Logistics and Artificial Intelligence (IA)" training program provides key skills to transform logistics through the use of artificial intelligence. Participants acquire abilities to automate logistics processes with robotics and RPA, manage data using Big Data, and apply predictive analytics to anticipate demand. They also learn to optimize delivery routes using advanced algorithms, implement cybersecurity strategies in automated systems, and apply ethical principles when using AI. Additionally, the program promotes the development of strategies to integrate smart technologies into the supply chain, maximizing operational efficiency and ensuring return on investment, with a vision towards Logistics 4.0 and the future of automation in the sector (*Formation logistique et intelligence artificielle (ia) - Centre d*, 2024).

7.3.4. CLOUD COMPUTING INTEGRATED INTO TRAINING PROGRAMS

Although many training programs focus on data analysis and management, few specifically address the field of Cloud Computing. One such program is the IT Project Coordinator (cloud infrastructures, applications, or data) (EQF 6). Among the activities targeted in this program are information security management, cloud infrastructure orchestration, deployment and maintenance of cloud computing services, as well as the implementation of security policies to protect data stored in a cloud infrastructure (‘RNCP38478 - Coordinateur de projets informatiques (infrastructures cloud, applicatives ou data)’, n.d.-b).

7.3.5. BLOCKCHAIN INTEGRATED INTO TRAINING PROGRAMS

A training program in the field of Blockchain has been identified: Blockchain Solutions Project Manager (EQF 6). The Blockchain Solutions Project Manager is responsible for designing, coding, and improving blockchain-specific systems using appropriate programming languages such as Solidity, C++, or JavaScript. Additionally, they develop web applications and frameworks, while also being responsible for analasing client needs and implementing robust and secure blockchain architectures.

With their in-depth expertise in blockchain and cryptography, these professionals contribute to the creation of innovative solutions across various sectors, such as finance, logistics, and healthcare. In close collaboration with other stakeholders, blockchain developers play a key role in managing blockchain projects, ensuring effective coordination to meet objectives and address client needs, while providing technically reliable and scalable solutions (‘RNCP40146 - Chef de projets en solutions blockchain’, n.d.).

7.3.6. IOT INTEGRATED INTO TRAINING PROGRAMS

The training program for IoT Solutions Designer and Integrator focuses on designing and implementing the architecture of connected devices, enabling them to send, receive, and process signals, information, or instructions. These devices are designed to address the specific challenges of businesses, based on their business, managerial, or operational needs. Depending on the case, this professional's goal is to facilitate the automation of activities, optimize business processes, or strengthen managerial decision-making (‘RNCP39237 - Concepteur intégrateur de solutions en Internet des objets (IoT)’, n.d.).

7.4. THE IMPACT OF TECHNOLOGIES ON PEDAGOGICAL METHODS

Digital transformation has profoundly changed the landscape of professional training, introducing innovative learning methods tailored to contemporary demands (actionfirst, 2023).

7.4.1. ARTIFICIAL INTELLIGENCE: PERSONALIZED LEARNING

Among these advancements, artificial intelligence (AI) plays a key role by offering personalized educational paths that adjust to each learner's pace and preferences. Adaptive learning systems, by assessing performance in real time, provide specific resources to address identified gaps.

7.4.2. VIRTUAL AND AUGMENTED REALITY: IMMERSION AND SAFE PRACTICE

Moreover, virtual reality (VR) and augmented reality (AR) create immersive environments that enable hands-on practice without real-world risks. These technologies are particularly beneficial in fields such as medicine, engineering, and defense, where they allow for the safe simulation of complex scenarios.

7.4.3. ONLINE PLATFORMS AND MOOCS: FLEXIBILITY AND ACCESSIBILITY

Online platforms and MOOCs (Massive Open Online Courses) have democratized access to education, offering unprecedented flexibility that allows individuals to learn at their own pace, regardless of geographical or time constraints. This expanded accessibility is essential to meeting the demands of an ever-evolving job market.

7.4.4. BIG DATA AND PERFORMANCE ANALYSIS: OPTIMIZED MONITORING

The use of Big Data and analytical tools enhances the monitoring and evaluation of training programs. By analysing large datasets on learner performance, institutions can refine their teaching approaches to optimize educational outcomes.

7.4.5. TOWARDS MORE EFFECTIVE TRAINING ALIGNED WITH THE JOB MARKET

The integration of technology into professional training makes learning more personalized, immersive, accessible, and measurable. As these tools continue to evolve, they promise to make training even more effective and aligned with the demands of the modern job market.

7.5. RESULTS OF SCM SURVEY SENT TO VET CENTRES

7.5.1. OVERVIEW OF THE SURVEY

To better understand how emerging digital technologies (Industry 4.0) and green transition trends are being integrated into Supply Chain Management (SCM) training, a dedicated survey was conducted among Vocational Education and Training (VET) centres in France, Germany, Italy, Slovenia, and Turkey. The aim was to assess the current level of digital adoption, identify gaps in training provision, and evaluate how these centres are preparing learners for the challenges of SCM 4.0.

The survey explored a range of dimensions including institutional size, sectors of activity, integration of technologies into curricula, industrial collaboration, investment strategies, and perceived obstacles. Special attention was given to the evolving role of teachers, missing skills among learners, and the influence of external factors such as industry demand and policy guidelines.

The analyses presented below will consider the data as a whole, that is, in absolute terms. However, since the number of responses varies significantly between countries, a relative analysis will also be used in many cases. This means considering the proportion that each response represents within the total responses from its country. This approach will allow for a more balanced and representative interpretation of the results.

Out of 70 VET centres contacted, 21 responded, providing valuable qualitative and quantitative data on the realities and perspectives of training providers across different national contexts.

7.5.2. SURVEY PARTICIPATION RATE AND DATA RELIABILITY

With a response rate of 30% from the 70 VET centres contacted, the results reveal trends that merit consideration (see the methodology chapter for detailed statistics).

Table 8. VET Centre Survey Response Distribution by Country

Toward	Country	Number of Companies	Number of answers
VET	FR	14	6
	GER	31	
	IT	2	2
	SI	15	5
	TR	8	8
Total VET		**70**	**21**

7.5.3. GENERAL INFORMATION ON THE SURVEYED TRAINING CENTRES AND THEIR REPRESENTATIVES

Among the surveyed centres, 33% have fewer than 500 learners, while the majority (67%) serve more than 500. Regarding annual graduation rates, 43% of the centres report graduating between 100 and 300 learners per year. Most of the responses (72%) were provided by teachers or trainers acting as representatives of their respective institutions.

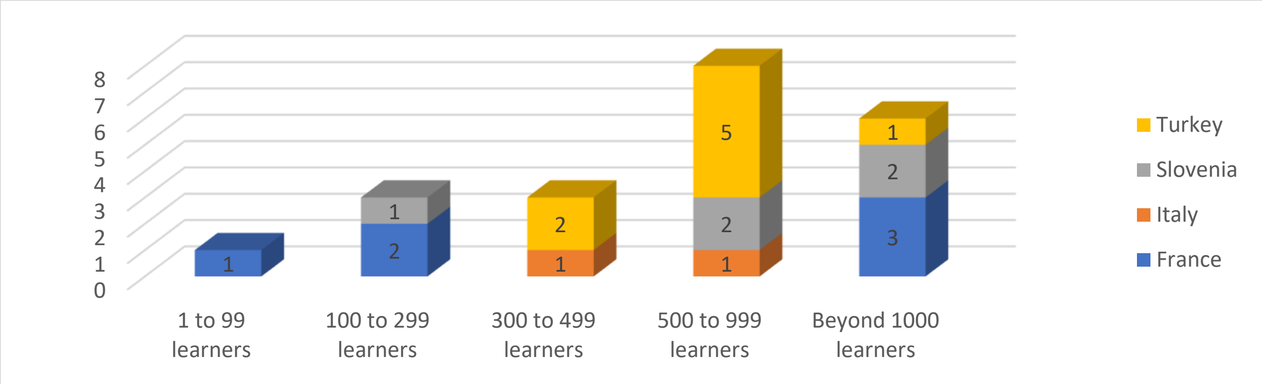

Figure 26. Size of your VET centre per country

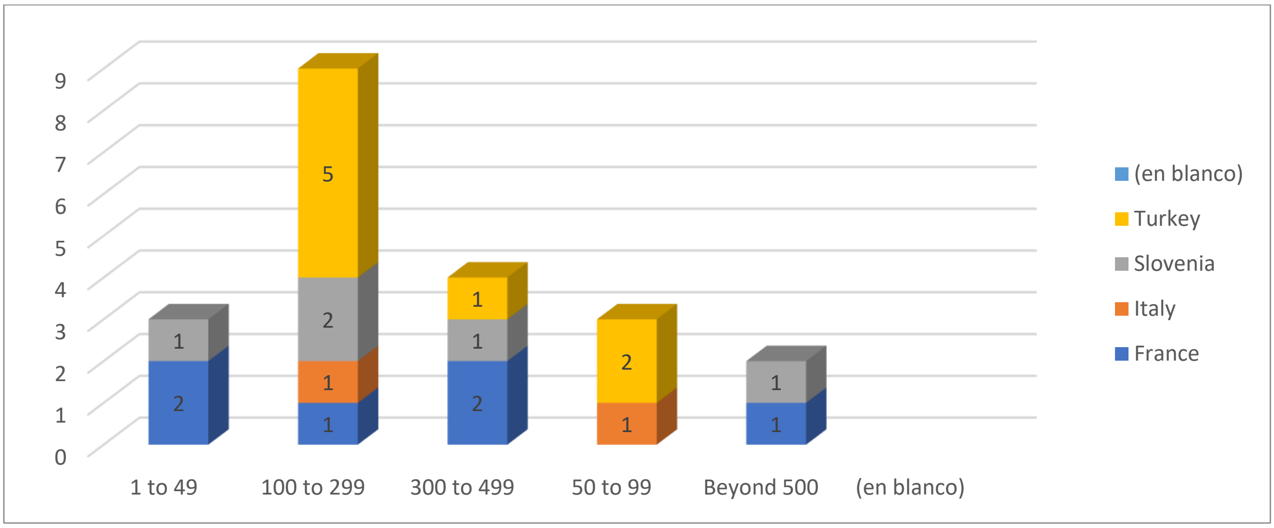

Figure 27. Number of learners graduate each year

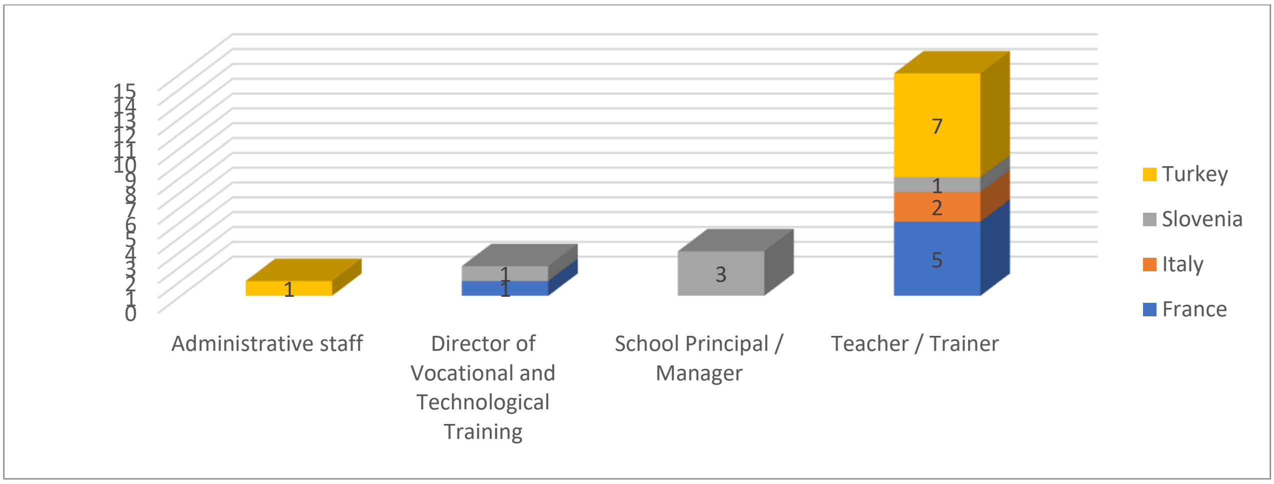

Figure 28. Roles within the VET Centre

7.5.4. LEVEL OF INTEGRATION OF 4.0 TECHNOLOGIES IN TRAINING PROGRAMMES

When asking training centres about the areas and technologies they plan to integrate into their programmes, the results show that the sectors of IoT, Sustainability, and Cybersecurity are the most prominent. The majority of the centres surveyed plan to take steps, whether in the short, medium, or long term, to incorporate these contents into their training programmes. The emerging technologies in the sectors of Operations Execution and Capacity Scheduling and Sales and Operations Planning, while also being integrated, do not seem to be a priority. Additionally, it is important to note that nearly all centres indicated that they have no plans to integrate content in areas outside of those mentioned. This suggests that the response options cover almost all sectors and technologies currently being integrated into training centres in the SCM field.

They were also asked about the next steps these training centres plan to take in order to continue integrating content related to emerging technologies into their programmes. The results show that the sectors of IoT, Sustainability, and Cybersecurity are the most prominent. The majority of the centres surveyed plan to take steps, whether in the short, medium, or long term, to incorporate these contents into their training programmes. The emerging technologies in the sectors of Operations Execution and Capacity Scheduling and Sales and Operations Planning**,** while also being integrated, do not seem to be a priority. Additionally, it is important to note that nearly all centres indicated that they have no plans to integrate content in areas outside of those mentioned. This suggests that the response options cover almost all sectors and technologies currently being integrated into training centres in the SCM field.

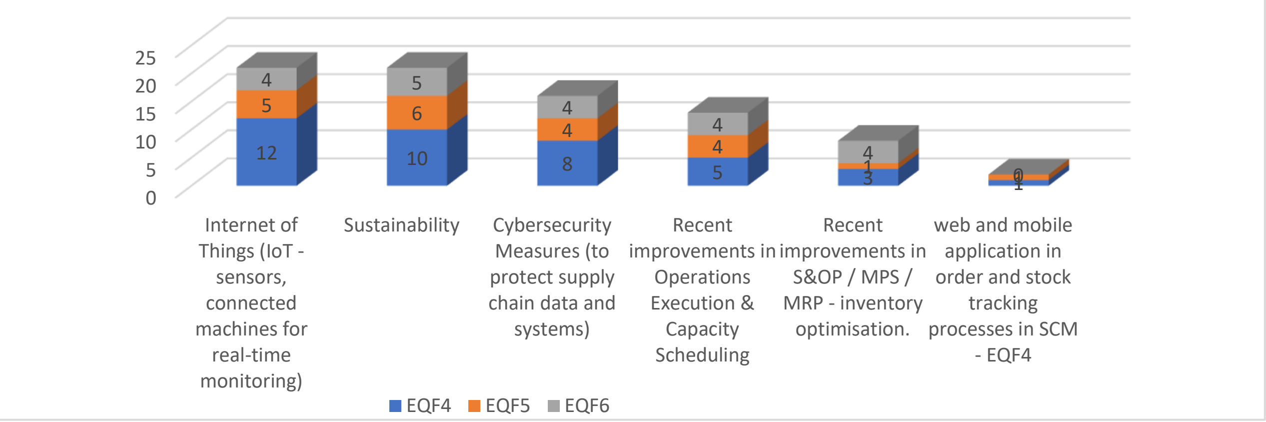

Figure 29. Courses taught in SCM integrating emerging technologies 4.0

7.5.5. REAL-TIME NEEDS AND PRACTICAL APPLICATION IN TRAININGS

Industrial partnerships emerge as the top choice for training centres when it comes to integrating real-time industrial needs, with 71% of centres opting for this alternative. Other options include practical experience (43%), the creation of specific modules (38%), and hybrid training (29%). When analyzing differences in the results by country, it can be observed that, unlike the general trend, Slovenia favors practical experience. Another interesting point is that only Slovenia and Turkey favor the option of hybrid training for the integration of real-time industrial needs.

Regarding the practical application of Supply Chain Management (SCM), most centres implement training modules based on business needs, with 62% of centres applying this strategy. Less commonly, with 43% of centres, are the creation of partnerships with industries that have integrated emerging 4.0 technologies and partnerships with other training centres. After analyzing the data by country, it becomes clear that, against the general trend, Turkey mainly favors partnerships with other training centres — an option that, in fact, is not favored by France in this regard.

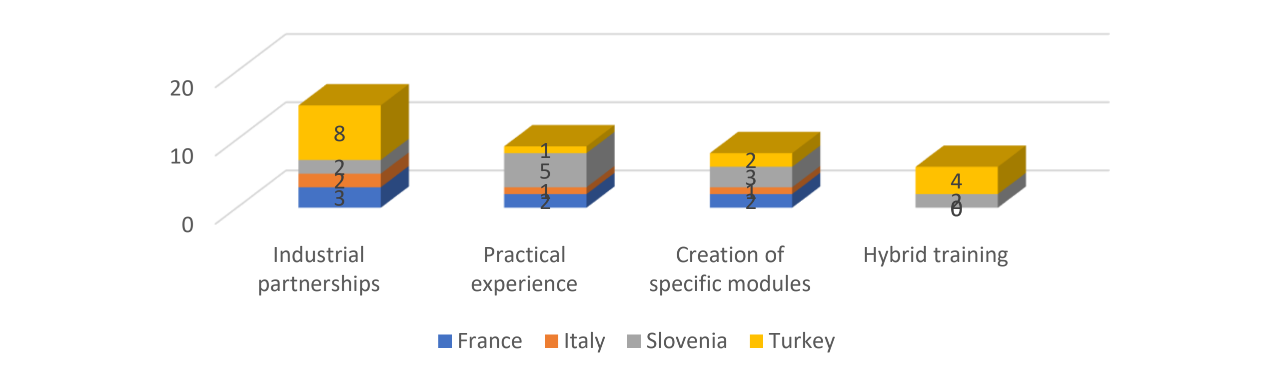

Figure 30. Opportunities or possibilities of VET centres foresee, or already foreseen, to integrate real-time industrial needs

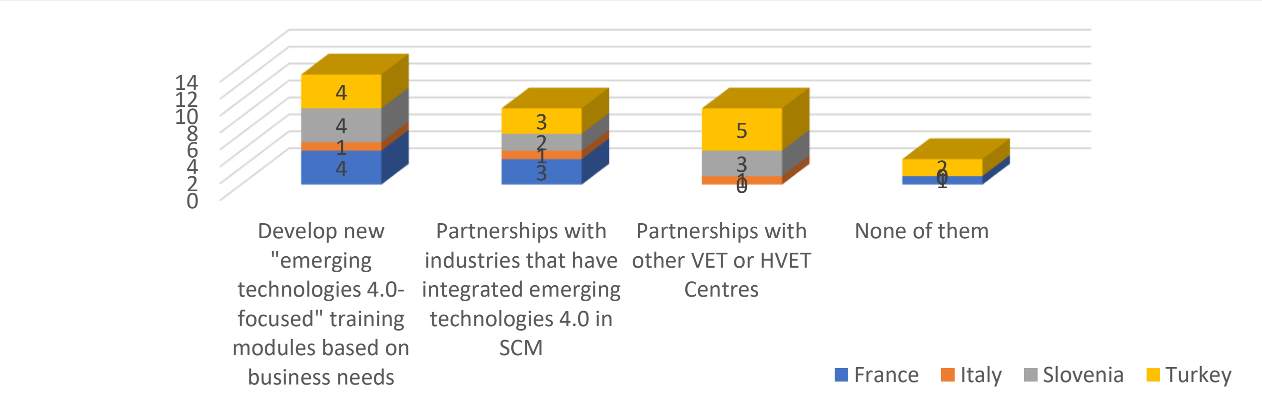

Figure 31. Approaches of VET centre to enhance the practical application of Supply Chain Management (SCM) concepts in supply chain training programs

7.5.6. FINANCIAL INVESTMENT AND FINANCIAL SOLUTIONS

Training centres were asked about the financial investment planned for integrating emerging technologies. The responses varied, with options such as 0%, 2%, 5%, 10%, 20%, and 30%. One centre mentioned that they plan to carry out the integration through Erasmus+ funding, and another through the central budget. A large number of centres indicated that they were unsure of the planned funding level; maybe because 72% of answers come from teachers, they are not able to provide such information.

As previously mentioned in this chapter, funding is often one of the main obstacles to integrating new technologies. Therefore, the centres were asked what financing solutions they were considering to carry out this task. 71% of the centres responded that they expect to do so through public funds. Additionally, 71% of the centres stated that they will resort to creating partnerships with the industry. Other strategies, although less commonly used than the previous ones, include sponsorship (24% of centres will use this strategy), own funds (24% of centres have available own funds), and European funding (1 centre plans to do so through the LCAMP European project they are involved in).

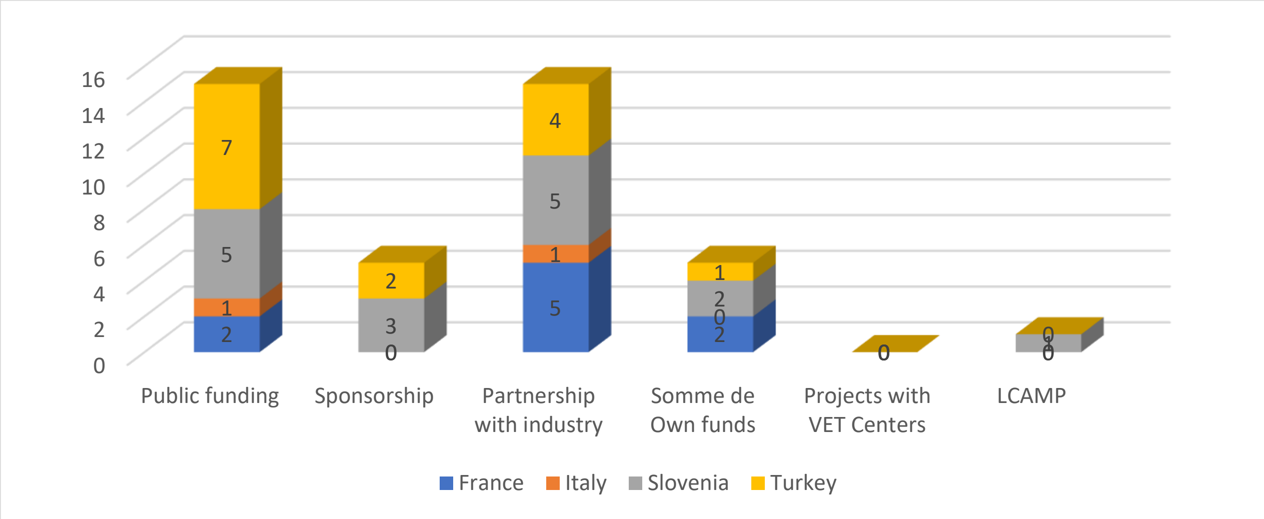

Figure 32. Financial solutions being considered to develop access to the digital emerging technologies 4.0 in SCM training programs (absolute figures)

7.5.7. TRAINING OF TRAINERS

In general terms and based on absolute values, the main way in which teachers stay up to date with technological advancements is through technology watch, used by 67% of the training centres. Other strategies include external training and certification (43%), practical workshops (33%), industrial immersion (38%), new technologies days in VET centres (43%), and the national education training plan (38%).

An interesting finding is that none of the French training centres surveyed reported using the national education training plan as a means of teacher training. It is also noteworthy that, when analysing the data in relative rather than absolute terms, significant differences between countries emerge: for instance, 55% of training centres in France cite technology watch as their main tool for identifying trends in 4.0 technologies, whereas in Turkey, most trainers stay updated through external training and certifications.

The data is presented below in both absolute and relative terms.

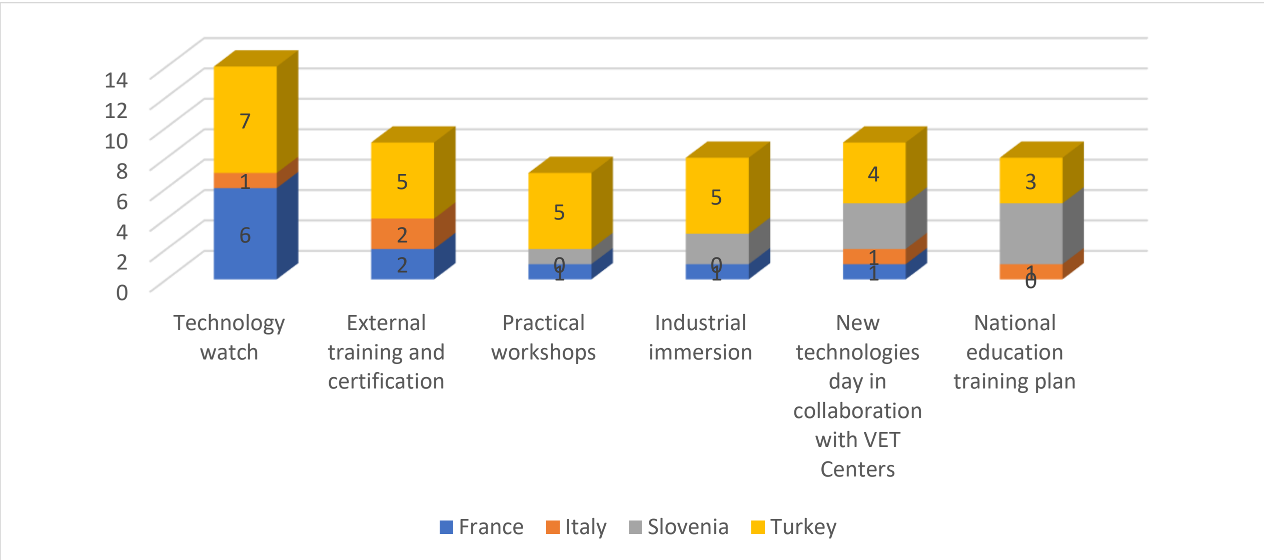

Figure 33. Strategies in place or necessary to ensure the training of trainers and teachers in advanced technologies (absolute figures)

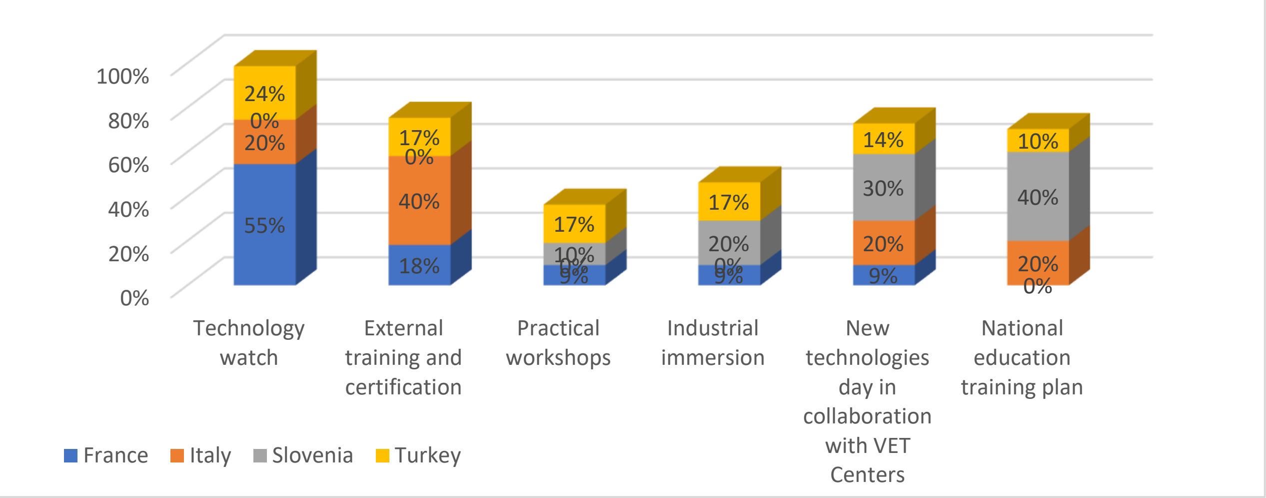

Figure 34. Strategies in place or necessary to ensure the training of trainers and teachers in advanced technologies (relative figures)

7.5.8. COLLABORATIONS

According to absolute data, most of the surveyed training centres maintain only occasional partnerships, with a significant proportion lacking any active collaboration. Only around 20% report having solid and sustained partnerships. However, when analyzing the data in relative terms, the picture becomes more nuanced: it becomes evident that the number of training centres maintaining occasional collaborations is much lower, and conversely, the number of centres with no active collaborations is much higher.

Regarding collaborations aimed at developing interdependent training pathways in the Supply Chain field, these are mainly established with the industrial sector or based on common training frameworks. Only 10% of centres engage in joint certifications, while a notable 30% have no plans to establish any collaboration of this kind. When analysing the data by country, it can be seen that, although the general trend favors industrial collaboration, countries like Turkey are more inclined towards common training frameworks. Another interesting finding is that 83% of French training centres do not foresee collaborations for the development of interdependent training paths.

Overall, 86% of surveyed centres believe that links with industry professionals could be strengthened to better align training content with the future needs of the Supply Chain Management (SCM) sector and related fields. Additionally, 67% support the regular review of training programmes in collaboration with industrial partners. However, none of the surveyed centres consider the role of an industrial advisory board to be important. When examining the same data in relative terms, it can be observed that, against the general trend, Turkey shows a greater preference for regular reviews of training programmes.

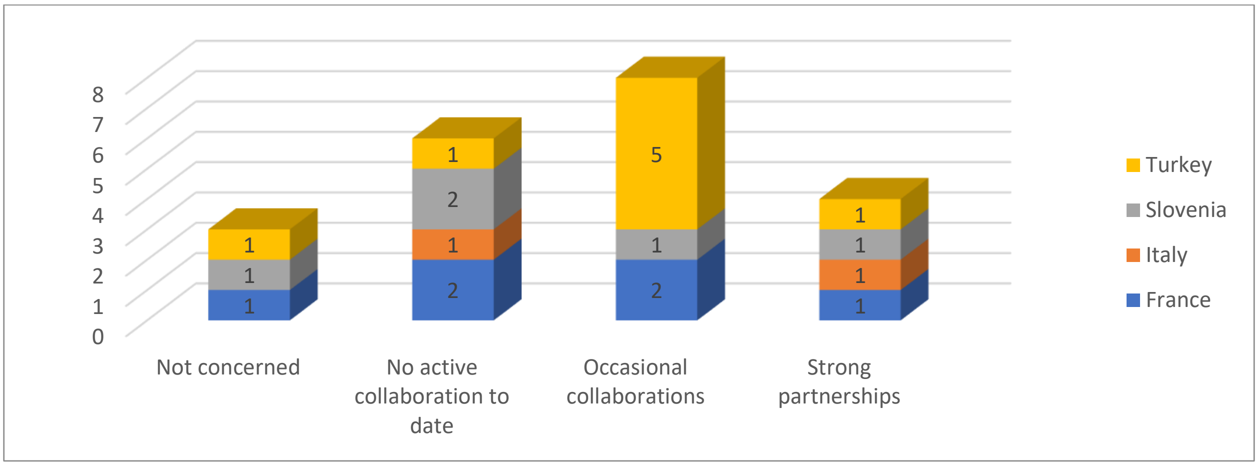

Figure 35. Collaboration strategies put in place or are being planned with other training centres and organisations to promote the consistency of Supply Chain training paths (absolute figures)

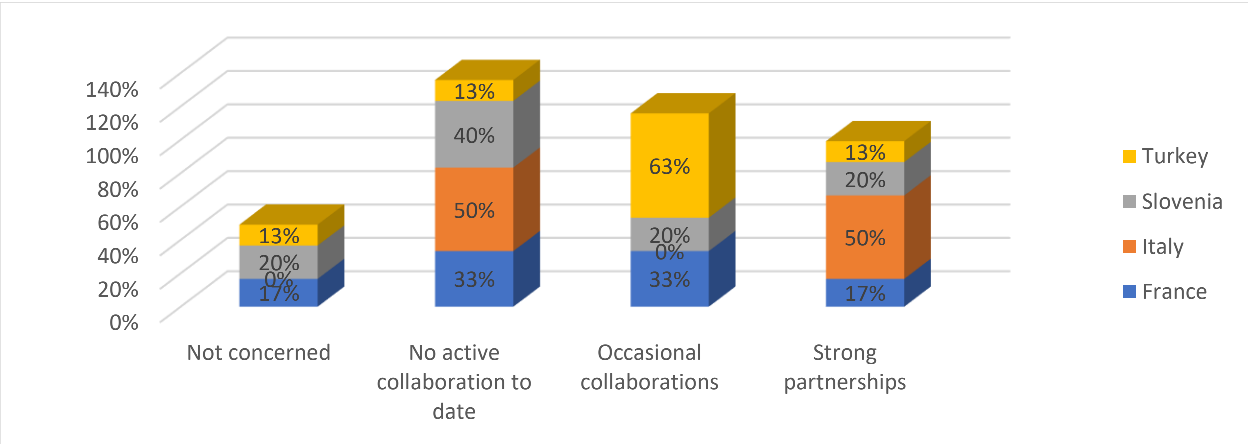

Figure 36. Collaboration strategies put in place or are being planned with other training centres and organisations to promote the consistency of Supply Chain training paths (Relative figures)

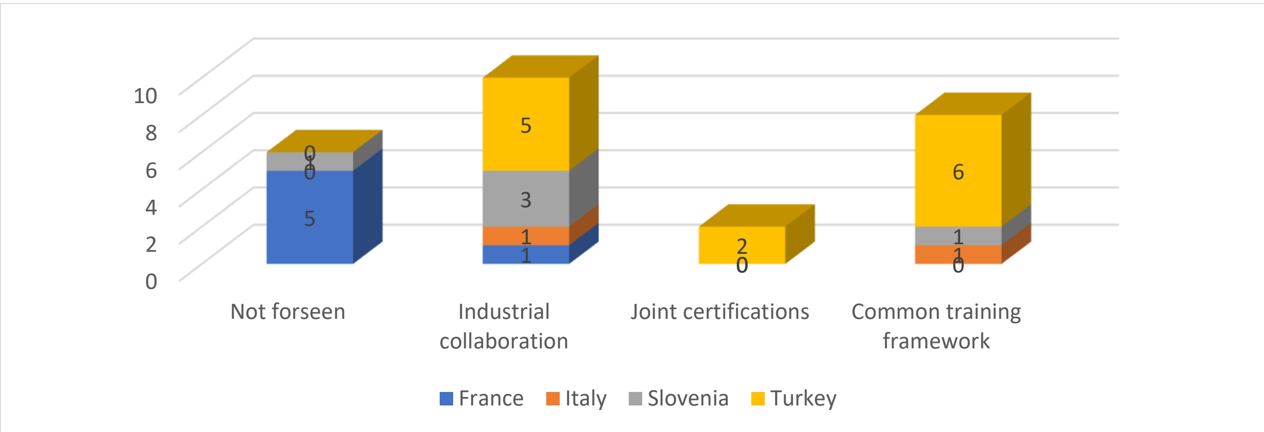

Figure 37. Development of interdependent training paths foreseen through collaboration between institutions with different areas of interest in Supply Chain training (absolute figures)

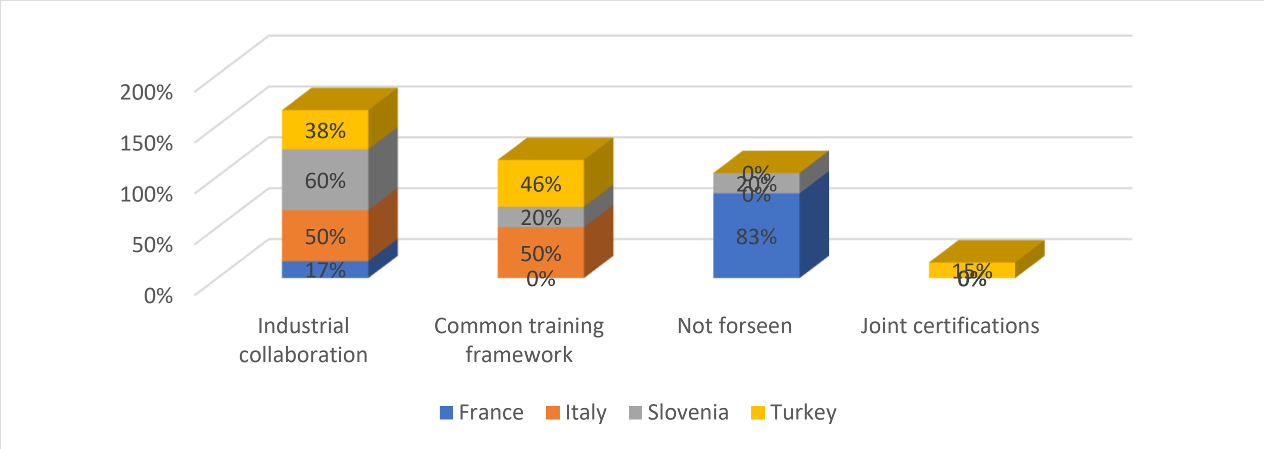

Figure 38. Development of interdependent training paths foreseen through collaboration between institutions with different areas of interest in Supply Chain training (relative figures)

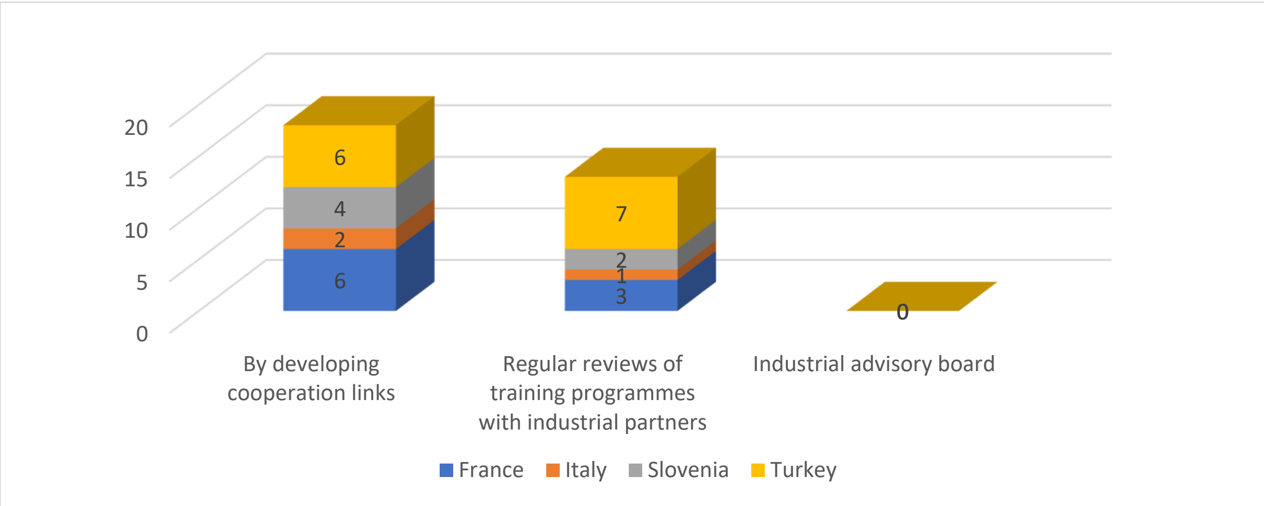

Figure 39. How can cooperation with industry professionals be strengthened to better align teaching content with current and future needs in SCM and related fields? (absolute figures)

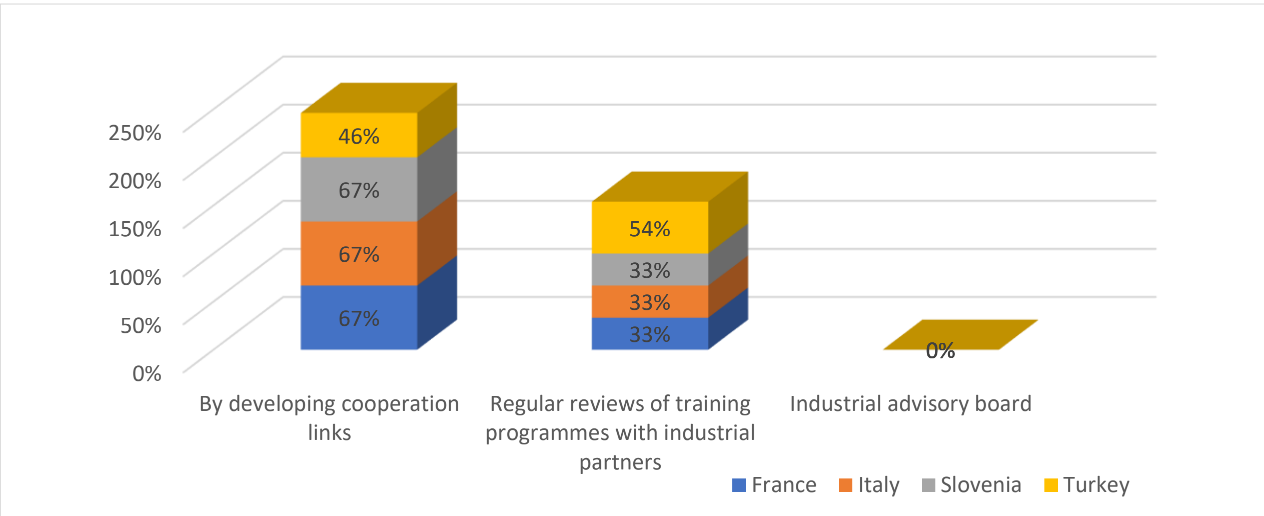

Figure 40. How can cooperation with industry professionals be strengthened to better align teaching content with current and future needs in SCM and related fields? (relative figures)

7.5.9. MAIN OBSTACLES TO INTEGRATE DIGITAL TECHNOLOGIES 4.0 INTO SCM TRAINING

The main obstacle for training centres in integrating emerging digital technologies 4.0 into Supply Chain Management (SCM) training is the lack of qualified trainers and the lack of training for them. 90% of the training centres shared this opinion.

The second main obstacle is the cost that adapting to new technologies entails, as previously addressed in this report.

Only 20% of the centres believe that there is limited demand, which could be seen as an obstacle. However, as mentioned in the previous chapter, the literature indicates that demand is more likely to increase, which might explain why only 20% of the centres chose this option. Nonetheless, it remains an interesting data point.

Regarding implementation complexity (subscriptions, data security, digital pollution, etc.), it seems that it is not a major concern for the training centres. None of them think this aspect could be considered an obstacle.

When reviewing the previously presented data on obstacles from a relative perspective, it becomes clear that the **lack of training for trainers** is the only major obstacle identified by training centres in **Italy**. For **France**, the main challenge is also the **lack of qualified trainers**, although to a lesser extent, the **cost of adapting to new technologies** is also mentioned. In contrast, training centres in **Turkey** and **Slovenia** report being impacted by a combination of factors: the **cost of technological implementation**, the **lack of qualified trainers**, and a **limited demand from learners**.

In absolute terms, only 29% of the centres have full autonomy, while the majority have limited or controlled autonomy, with even one centre reporting no autonomy at all. This situation arises because many centres depend on the State and ministerial guidelines. As discussed earlier, this leads to greater dynamism in the private sector, which is not subject to the bureaucratic procedures and decision-making processes of public institutions. When observing this data in relative terms, it can be seen that the simple majority of training centres in countries such as France or Turkey enjoy full autonomy.

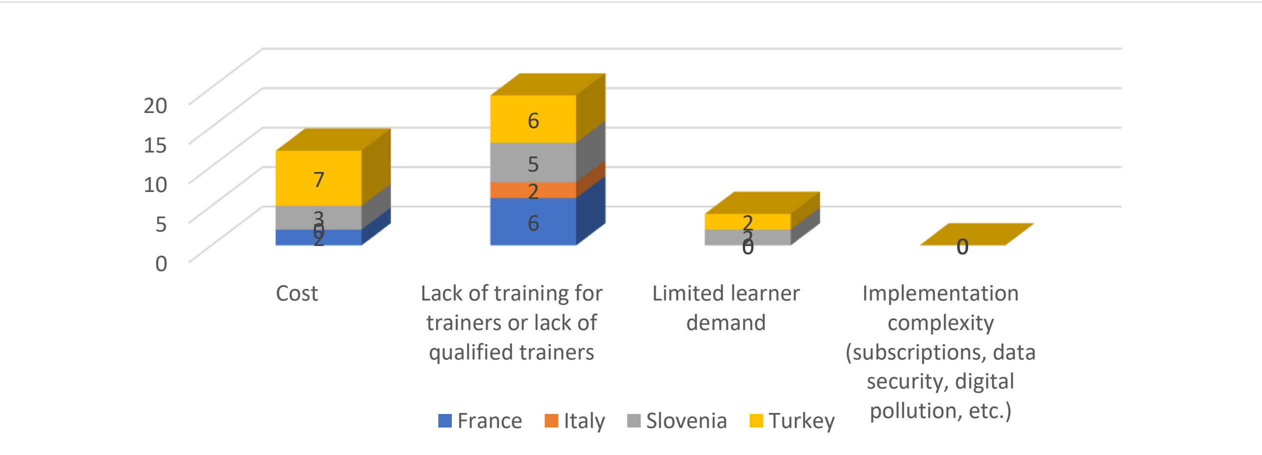

Figure 41Main obstacles to integrate emerging digital technologies 4.0 into SCM training (absolute figures)

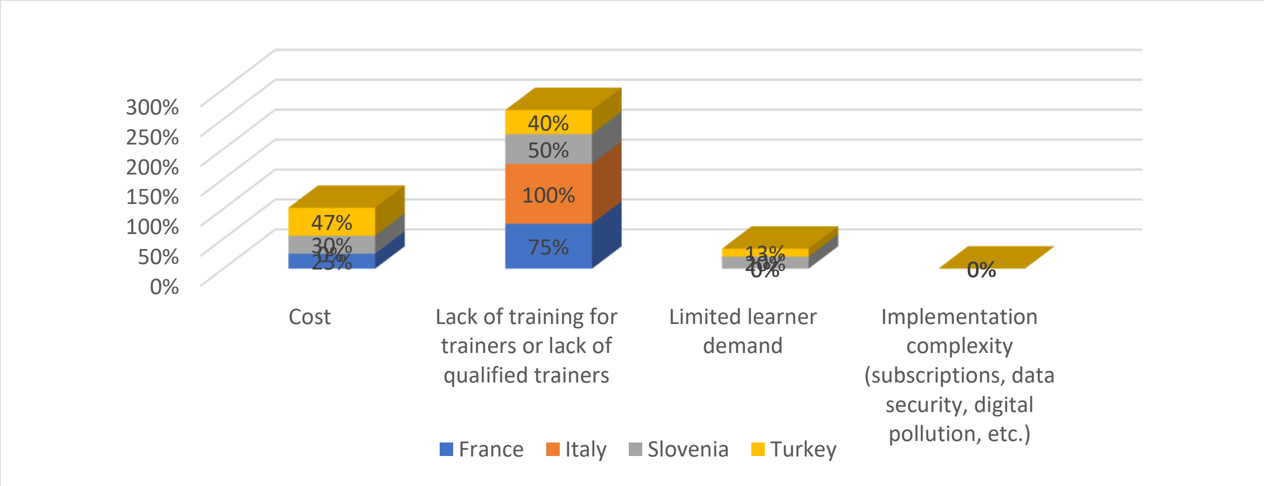

Figure 42. Main obstacles to integrate emerging digital technologies 4.0 into SCM training (relative figures)

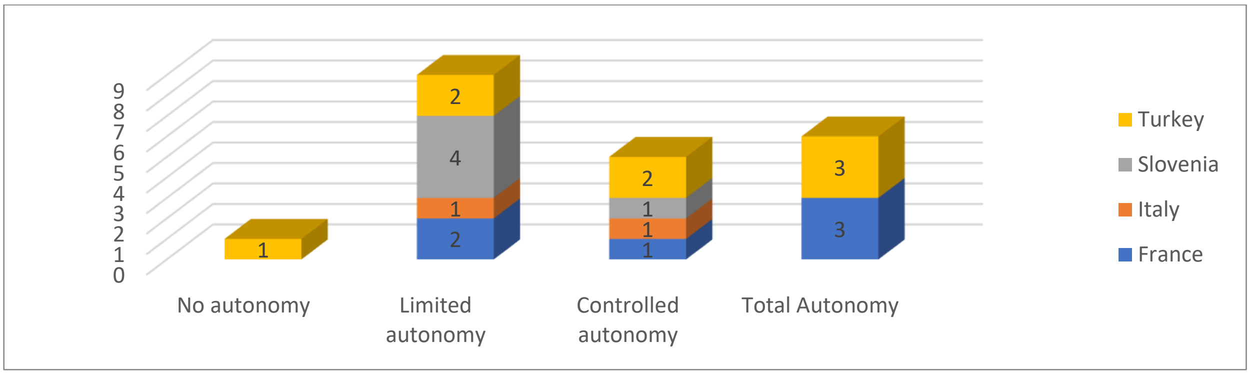

Figure 43. Capacity of VET centre to adapt its training content to the evolution of emerging digital technologies 4.0 such as IoT, AI, cybersecurity, and sustainability in supply chain jobs (absolute figures)

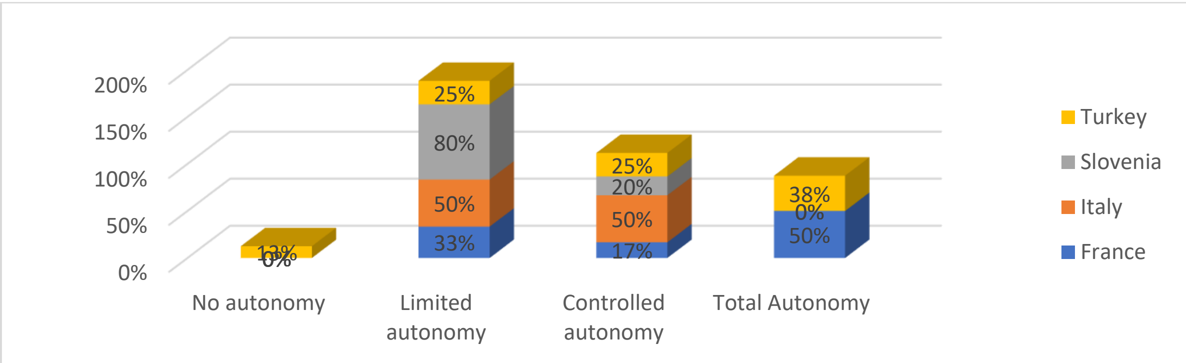

Figure 44. Capacity of VET centre to adapt its training content to the evolution of emerging digital technologies 4.0 such as IoT, AI, cybersecurity, and sustainability in supply chain jobs (relative figures).

7.5.10. EXTERNAL FACTORS INFLUENCING THE INTEGRATION OF EMERGING DIGITAL TECHNOLOGIES 4.0 INTO PROGRAMS

Nearly **70%** of the training centres believe that **technological advancements** and **industrial demand** are the factors that most influence the integration of **emerging digital technologies** into programmes. Only **40%** of the centres think that **academic and governmental guidelines** are an important factor in this regard. Additionally, only **10%** of the centres believe that **competitors' offerings** are also a determining external factor of influence.

In the chart presenting the same data in relative terms, it can be seen that while technological advancements are viewed as the most important external factor in countries like Italy, in countries such as France and Turkey, the main factor is industrial demand.

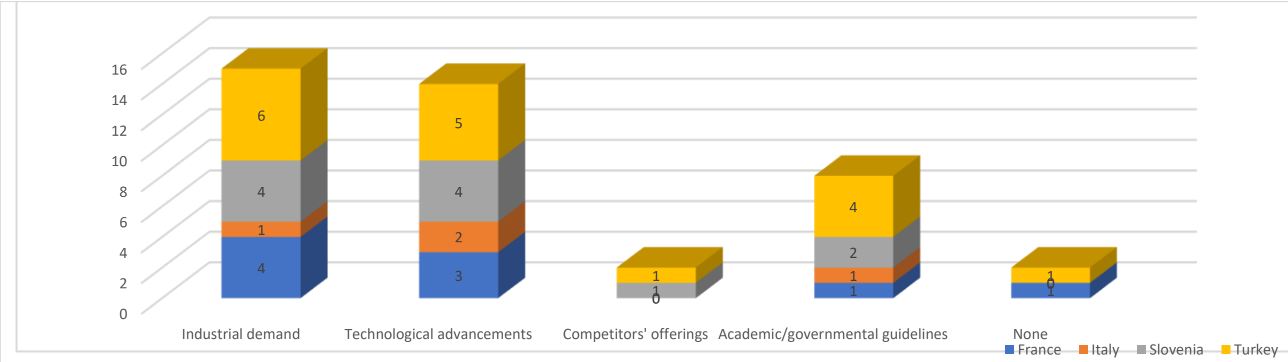

Figure 45. External factors influencing the integration of emerging digital technologies 4.0 into programs (abolute figures)

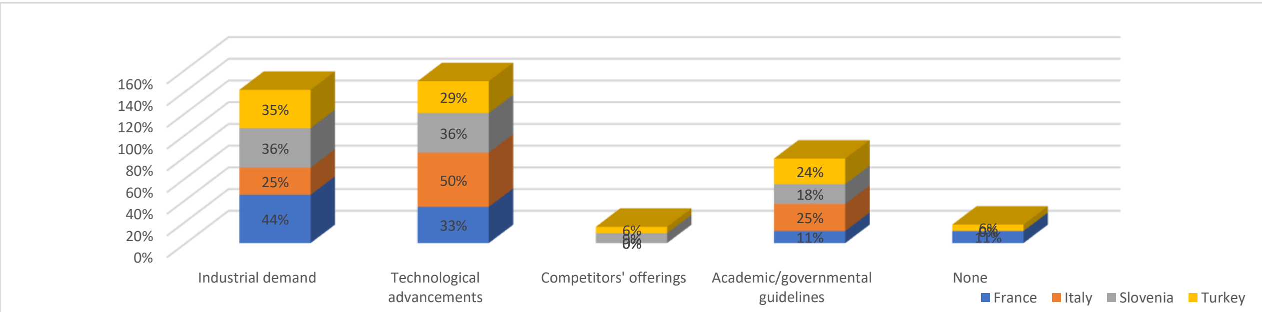

Figure 46. External factors influencing the integration of emerging digital technologies 4.0 into programs (relative figures)

7.5.11. MISSING SKILLS AND PEDAGOGICAL RESOURCES

Based on the surveys, it has been determined which are the main **missing skills** among learners for **SCM** positions involving the use of **digital technologies 4.0**. The results revealed that nearly **70%** of the training centres believe that the main missing skills are the use of **IoT systems**, the use of **AI tools**, and **data analysis**. On the other hand, **40%** of the centres selected the use of **cloud-based computing**, and only **14%** believe that **teamwork collaboration** is a missing skill, which suggests that most training programmes are adequately focused on teaching this soft skill (collaborative work). By analyzing this data in relative terms, it can be observed that for France, the main missing skills are the use of AI tools and data analysis; for Italy, it is the use of IoT systems; for Turkey, it is cloud computing and data analysis; and for Slovenia, it is the use of IoT systems and the use of AI tools.

Regarding the **pedagogical resources** considered most effective for teaching in the area of **emerging technologies 4.0**, **practical tools** are the most prominent, followed by **conferences and workshops**, with **online resources (MOOCs)** being ranked last.

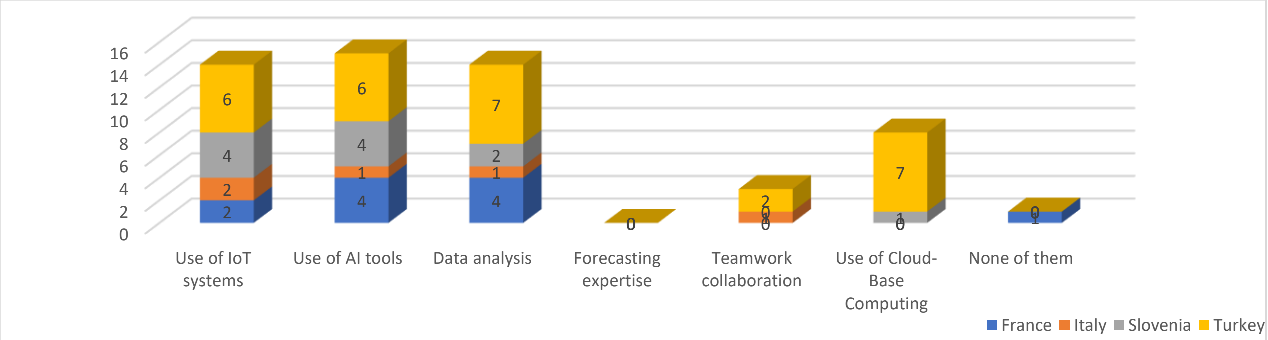

Figure 47. Skills missing among learners for SCM positions involving the following emerging digital technologies 4.0 usage (absolute figures)

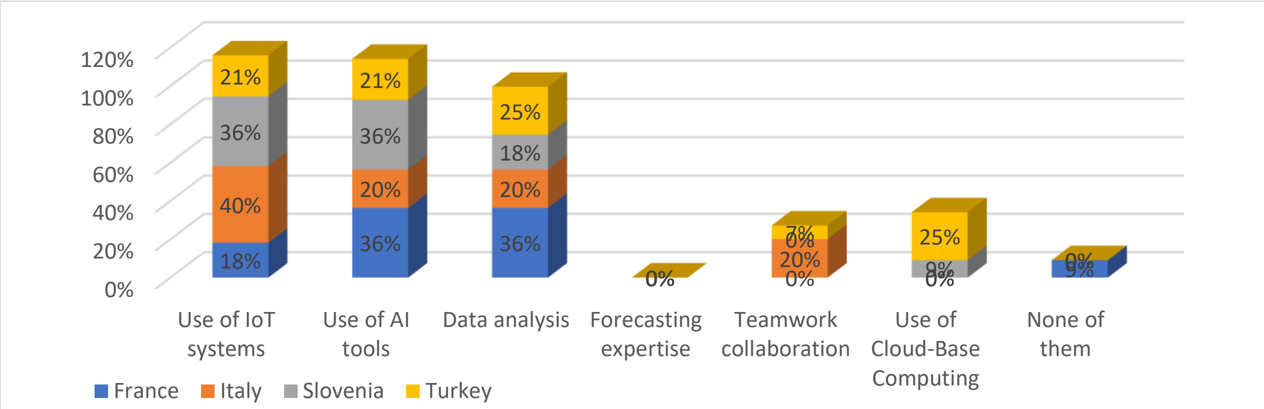

Figure 48. Skills missing among learners for SCM positions involving the following emerging digital technologies 4.0 usage (relative figures).

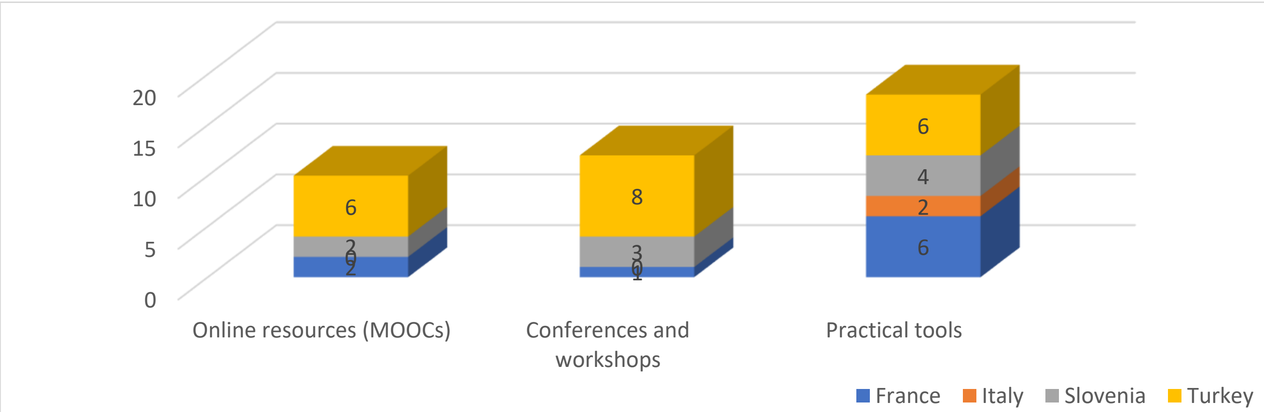

Figure 49. Types of emerging digital technologies 4.0 training resources which would be most effective for learners (absolute figures).

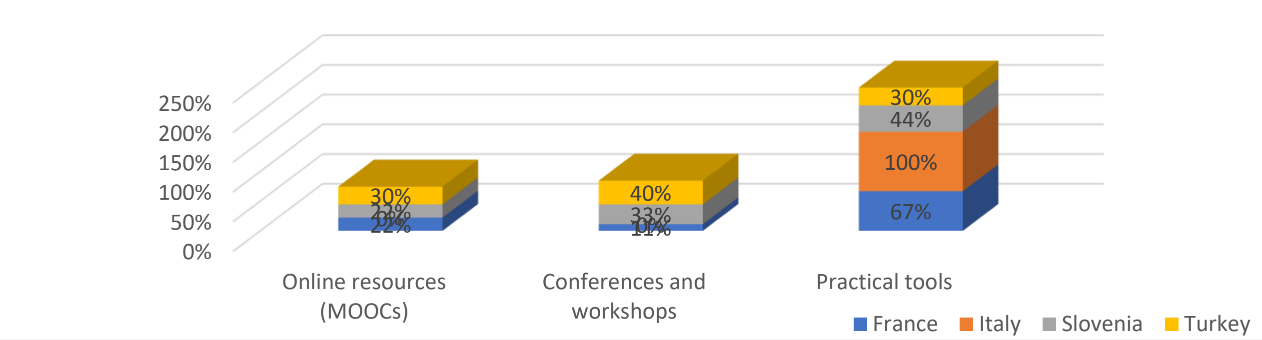

Figure 50. Types of emerging digital technologies 4.0 training resources which would be most effective for learners (relative figures).

7.5.12. FREE COMENTS FROM SURVEYED VET CENTRES

An open-ended question allowed to receive some feedback from representatives of training centres in Turkey and France.

The representatives from training centres in Turkey shared the following:

- "The Ministry should make the training of teachers in the area of digital and green transformation in all vocational training institutions mandatory."
- "As an educational institution, we are working both with our own efforts and with the collaboration of our international partners. However, school curricula are insufficient in this regard. It is crucial that *artificial intelligence tools* are taught across all vocational branches."
- "The **Horizon Europe Strategic Plan 2025-2027** emphasizes the need to take action against climate change, global warming, and health threats within the framework of **twin transformation**. The **Erasmus+ 2024 call** also aims to incorporate skills related to **digital transformation** and **green transformation**, which are part of the twin transformation, into educational environments, thus promoting the development of these skills. In this context, the **Erasmus+ 2024 call** prioritizes the development of a digital ecosystem that facilitates the opportunities offered by digital technologies.

  Digital transformation *and* ***green transformation*** *skills are key to ensuring sustainability in* ***production****,* ***production planning*** *that respects the environment and people, and the establishment of* ***sustainable logistics networks****."*

The representatives from training centres in France shared the following:

- *"It is essential to develop* ***skills*** *rather than* ***knowledge****. There is a growing interest in creating programmes that combine* ***initial training*** *with* ***vocational training****. Furthermore, there is interest in using* ***AI*** *and* ***XR*** *not only as training tools but also as* ***aids*** *for the educational process."*

7.6. CONCLUSION AND OUTLOOKS

Technologies 4.0 have had a significant impact on Supply Chain Management (SCM). Their influence on training centres and SCM programs — as illustrated throughout this report and in the training chart included in the annexes — brings both opportunities and challenges, driving the emergence of new professions and greater specialization in both industry and education.

The automation of manual tasks has shifted training focus towards competencies in analysis and management, while promoting greater flexibility and accessibility through hybrid learning models that also encourage networking and professional integration.

The growing demand for training has led to a proliferation of new program offerings, with most training centres not perceiving the lack of demand as an obstacle. This trend represents a major opportunity, pushing centres to continuously update their programs based on industry needs and strengthening collaborations with companies - 71% of centres report opting for industrial partnerships to integrate real-time industrial demands into their curricula. Similarly, other 71% plan to establish such partnerships to secure funding for adapting to emerging technologies.

Despite strengthened ties with industry, collaborations between training centres themselves remain rare, as most prefer industrial partnerships over joint certifications. Centres also face significant financial constraints and limited autonomy, with only 29% enjoying full decision-making freedom, often restricted by public institutions and bureaucratic processes. Although these challenges slow technological adaptation, they sometimes offer an advantage to private training providers. Nevertheless, the most critical obstacle identified remains the lack of proper training for trainers and teachers, a challenge already highlighted in previous studies.

Another major issue is the persistence of "missing skills": nearly 70% of training centres report gaps in the use of IoT systems, AI tools, and data analysis. Additionally, 40% cite cloud computing as a missing skill, while only 14% point to teamwork, suggesting that soft skills development is generally well addressed. Country-specific trends reveal that France mainly lacks skills in AI and data analysis, Italy struggles with IoT, Turkey with cloud computing and data analysis, and Slovenia with both IoT and AI tool usage.

Representatives from training centres in Turkey and France have stressed the urgent need for mandatory teacher training in digital and green transformation, as well as the integration of AI tools across all vocational fields. They emphasize that current curricula remain insufficient, despite efforts made through international partnerships. Key initiatives such as the Horizon Europe Strategic Plan 2025–2027 and the Erasmus+ 2024 call are seen as crucial supports for the development of digital ecosystems and sustainability skills. Additionally, there is an increasing focus on developing practical skills over theoretical knowledge, promoting programs that combine initial and vocational training, and using AI and XR technologies to enhance the educational process.

8. SCM 4.0: A DRIVING FORCE FOR THE GREEN TRANSFORMATION

As environmental challenges intensify and regulatory pressures mount, companies are increasingly integrating sustainability into their operational strategies. The convergence of **Supply Chain Management 4.0 (SCM 4.0)** and **green supply chain practices** represents a powerful lever for achieving sustainable transformation. SCM 4.0—powered by technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), cloud/edge computing, and blockchain—is redefining how organisations manage resources, measure environmental impact, and drive eco-innovation across supply networks.

8.1. THE RISE OF GREEN SUPPLY CHAIN MANAGEMENT (GSCM)

Green Supply Chain Management (GSCM) incorporates environmental considerations into every stage of the supply chain, from product design to sourcing, manufacturing, logistics, and end-of-life processes. Empirical studies across sectors such as textiles, automotive, and tobacco show that initiatives like green purchasing, eco-design, and environmental information systems lead to improved sustainability performance (Phonthanukitithaworn et al., 2024)

- **IoT adoption** improves energy and waste tracking, leading to a **12–20% reduction in material waste** across pilot cases.
- **AI-supported logistics optimisation** contributes to a **5–10% decrease in CO_2 emissions** through better route planning and load balancing.
- **Blockchain-enabled traceability** increases the share of recycled materials used in production by up to **15%**, due to improved transparency and supplier accountability.
- **73% of surveyed firms** reported that digital tools had **"moderate to high impact"** on their sustainability performance.
- Only 27% of firms had formally integrated sustainability and digital transformation strategies, suggesting strong potential for alignment improvement.

A comprehensive review by ResearchGate authors emphasizes that GSCM is no longer optional - it is integral to long-term competitiveness and compliance with global ESG (Environmental, Social, and Governance) frameworks. According to the **Resource-Based View (RBV)**, firms with dynamic capabilities - such as the integration of digital and green resources - gain sustainable competitive advantage (Mehmood Khan et al., 2022).

8.1.1. DIGITAL TECHNOLOGIES AS ENABLERS OF THE GREEN TRANSITION

The transformative power of **SCM 4.0** lies in its ability to make supply chains more **visible, intelligent, and responsive**. These characteristics are critical in accelerating green performance and operational resilience.

8.1.2. IOT & REAL-TIME ENVIRONMENTAL MONITORING

IoT sensors enable real-time tracking of energy usage, emissions, and waste across operations. This data allows for dynamic adjustments to processes and improved resource efficiency.

Example: Smart energy meters and temperature sensors in cold chain logistics reduce energy waste and optimize fuel use.

8.1.3. ARTIFICIAL INTELLIGENCE FOR GREEN OPTIMIZATION

AI enhances decision-making in sustainable sourcing, demand forecasting, and route optimization. It enables simulation of carbon footprints across supply chain scenarios, promoting better design and distribution strategies.

Study: AI algorithms used in logistics have reduced fuel consumption by 10–15% in pilot projects (Mir & Dwivedi, 2024).

8.1.4. CLOUD/EDGE COMPUTING FOR SUSTAINABLE INFRASTRUCTURE

Cloud and edge computing reduce the need for physical infrastructure, lowering energy demand and facilitating decentralized, data-efficient systems. They also enable the integration of ESG analytics tools.

8.1.5. BLOCKCHAIN FOR TRANSPARENCY AND TRACEABILITY

Blockchain technology enhances visibility and verifiability of green certifications, ethical sourcing claims, and carbon offset initiatives, reducing greenwashing risks.

8.1.6. KEY PILLARS OF GREEN SCM TRANSFORMATION

8.1.6.1. SUSTAINABLE SOURCING

Prioritizing environmentally responsible suppliers helps reduce upstream emissions. Supplier scorecards based on CO_2 impact, energy efficiency, and labor practices are increasingly common.

8.1.6.2. ENERGY-EFFICIENT LOGISTICS

SCM 4.0 enables route optimization, modal shifts (e.g., rail over road), and alternative energy use (e.g., electric fleets), significantly cutting logistics-related emissions.

Insight: According to the World Economic Forum (2023), transport accounts for over 25% of global CO_2 emissions, making logistics a key leverage point for sustainability.

8.1.6.3. CIRCULAR ECONOMY INTEGRATION

Technologies facilitate closed-loop systems, enabling reuse, remanufacturing, and recycling. Predictive analytics help design reverse logistics networks and monitor product life cycles.

8.1.6.4. ECO-DESIGN & GREEN PRODUCT INNOVATION

SCM 4.0 allows real-time collaboration across the supply chain during product development, integrating sustainability into the DNA of new products - from materials to recyclability.

8.1.7. CHALLENGES AND STRATEGIC RECOMMENDATIONS

While the alignment of digital and green agendas holds great promise, several challenges remain for SMEs and larger enterprises alike:

- **Digital Readiness Gaps**: Many SMEs lack the infrastructure or skills to implement SCM 4.0 effectively (Eurostat, 2023).
- **Data Silos & Fragmentation**: Achieving holistic sustainability metrics requires seamless data integration across functions and partners.
- **Cost-Benefit Ambiguity**: Investments in green technologies and digital tools can pose risks if ROI is not clearly articulated or supported by incentives.

8.2. SCM 4.0 AS A CATALYST FOR GREEN INDUSTRIAL CHANGE

SCM 4.0 provides a unique opportunity to align economic competitiveness with environmental stewardship. Far from being parallel agendas, digitalization and sustainability are **mutually reinforcing** when strategically implemented. Organisations that embed green principles into their digital supply chain strategies are better positioned to comply with environmental regulations, attract ESG-conscious investors, and meet evolving customer expectations.

The future of supply chain competitiveness will depend not just on speed and cost-efficiency, but on resilience, transparency, and responsibility. SCM 4.0, when paired with sustainability, is the foundation for the **next generation of ethical and intelligent supply chains**.

9. EXPERTS' EVALUATION

Contributing Experts and methodology:

The following experts, all actively engaged in the field of Training and/or Supply Chain Management, provided insights and evaluations based on their level of experience and involvement.

Table 9. List of experts who contributed to the assessment of the report

Country	Expert name	Role/position
France	Stéphane Blanchard	Mission officer – Industry 4.0 - AD'OCC
	Vincent Nourrisson	Transformation Architect - CETIM
	Pierre Carillo	Professor - IUT Limousin
	Patrick Fauchère	Professor - IUT Limousin
Slovenia	Samo Čretnik	Professor and head of school - TŠCMB
	Igor Hanc	Expert and director - ŠC Škofja Loka
Germany	Prof. Dr..-Ing. M.S. Reinhold Bopp	Professor from the Faculty of Economics and Law at the University of Applied Sciences in Geislingen-Nürtingen (HfWU)
Turkey	Sema Kurt	Logistic Teacher
	Elif Ademoğlu	Logistic Teacher
	Ibrahim Birol	Logistic Teacher
	Taner Dogan	Human Resources and Administrative Affairs Manager
	Bulut Yilmaz	Sustainability and Management Systems Manager
	Görkem Akin	Occupational Health and Safety Specialist
	Ali Kemal Yükek	Production Chief
	Harun Künü	School Manager
Italy	Beatrice Colombo	Researcher at the University of Bergamo - Department of Management, Information and Production Engineering
	Alberto Salioni	Professor at ITS Torricelli
	Tiziano Fapanni	Researcher at the University of Brescia - Department of Electrical and Electronic Engineering

Experts quotation:

The report received a **positive overall evaluation**, with an average score of **3.59 out of 4 and** a general feedback score of **3.80 out of 4**.

across all expert responses. This high score reflects the report's **relevance, clarity, and usefulness** to both industrial stakeholders and training institutions, although the sample sizes of the two surveys was mentioned as pretty small, making the results somewhat questionable.

The following two tables present the quantitative evaluation of the report: the first one summarises average scores by **thematic category**, while the second provides average scores **per chapter**, based on expert feedback from the three participating countries.

Table 10. Quantitative Evaluation per category – (detail available in Annex 3):

Evaluation by category	Averages out of 4
Alignment with Industry and Training Needs	3,67
Clarity of Purpose and Structure	3,62
Relevance and Insightfulness of Content	3,64
Understanding of Methodology and Analytical Approach	3,18
Usefulness of Surveys and Data Interpretation	3,45
Overall Total	**3,59**

Table 11. Quantitative Evaluation per chapter – (detail available in Annex 3)

Chapter	Total
Chapter 1: **Introduction**	3,35
Chapter 2: **SCM – Scope & definitions**	3,68
Chapter 3: **SCM – Context**	3,82
Chapter 4: **Digital Solutions for SCM 4.0**	3,68
Chapter 5: **Leveraging Emerging Digital Technologies for SCM 4.0**	3,57
Chapter 6: **Impact of SCM 4.0 on SMEs**	3,51
Chapter 7: **Impact of SCM 4.0 on training AND tRAINING cENTRES**	3,55
Chapter 8: **SCM 4.0: A driving force for the green Transformation**	3,75
Chapter 10: **Conclusion and Outlooks**	3,87
General feedback	3,80
Overall Total	**3,59**

Chapter 3, which provides a **comprehensive overview of the current economic, geopolitical, and environmental context**, was valued for effectively **framing the urgency of digital and green transformation** in supply chains. It was seen as a solid foundation that helps readers understand why such changes are needed.

The sections covering the **impact of digital technologies** (Chapters 4 and 5) were rated highly for their relevance and depth. Additionally, the **recommendations aimed at SMEs and training centres** (Chapters 6 and 7) were considered actionable and well aligned with the needs of their target audiences.

Overall, the report is recognized for its **high relevance, clear structure, and strategic value**, with average evaluation scores approaching the highest ratings across most sections.

Main Recommendations and Areas for Improvement:

Despite the overall positive feedback, several constructive suggestions were made to strengthen the clarity, coherence, and accessibility of the report:

- **Structural consistency**: Some chapters were perceived as **too fragmented**, which occasionally disrupted the narrative flow. Experts recommended ensuring a more even distribution of detail and content across chapters.

- **Practical examples and illustrations**: Reviewers called for a broader use of **case studies, visual elements**, and **real-world examples** to better illustrate key points and make the content more accessible, especially for VET audiences and SMEs.
- **SME inclusiveness**: The conclusion, while appreciated for its clarity, was viewed as being too **oriented toward large enterprises**, with **limited reflection of SME realities**. More emphasis on the specific challenges and opportunities for SMEs would make the report more representative.

Integration of Expert Input:

Expert feedback played a key role in refining and strengthening the report. **Taking expert comments into account, the following points have been integrated into the final version**: an updated list of acronyms, as well as the addition of two new sections — Chapter 6.5.1, which addresses trust between vendors and customers, and Chapter 4.2.2, which focuses on the OPC Unified Architecture protocol. **Other suggestions provided by the experts may be considered for inclusion in a future version of the report.**

Projections and Recommendations for Future Reports:

French experts recommend involving stakeholders **earlier in the process**, particularly during the **definition of scope and structure**. They acknowledged that it is easier to criticize an existing structure than to create one from scratch, and therefore propose their **early engagement in validating the report's analytical framework**.

10. CONCLUSION AND OUTLOOKS

This report, based on an extensive literature review, expert interviews, and targeted surveys with VET centres and industrial companies, examines how emerging digital technologies and sustainability imperatives are transforming Supply Chain Management (SCM) – called SCM 4.0 in this report - in Europe. In accordance with industrial needs specific the the report focused on strategic and operational processes - such as Profit Planning (PP), Sales and Operations Planning (S&OP), Master Production Scheduling (MPS), Material Requirements Planning (MRP), and capacity scheduling (FCS/ICS) - it captures the profound shift underway across supply chains.

Over recent years, SCM has been deeply reshaped by the convergence of Industry 4.0 technologies and the demands of the green transition. This dual transformation is accelerating: digital solutions now enable smarter, faster, and more transparent supply chains, while sustainability requirements push organisations to adopt circular, low-carbon models. AI, IoT, cloud and edge computing, blockchain, and digital twins are no longer optional but strategic drivers of agility and resilience. The new generation of workers and consumers expects sustainable operations "from cradle to grave", making SCM 4.0 a core component of business competitiveness and responsibility.

Chapters 1 to 3 – Foundations and Context

These chapters provide definitions and context for SCM transformation. Industry 4.0 is driving a self-reinforcing cycle between technological progress and labour market evolution, creating growing demand for professionals with interdisciplinary skills in data, logistics, and sustainability. The convergence of digital innovation and market needs is reshaping both business models and workforce expectations.

Chapter 4 – Digital Solutions for SCM 4.0

A wide array of digital technologies is modernising SCM functions. This chapter stresses the need to balance automation with human oversight. AI-powered systems can greatly improve planning, inventory, and coordination - but only if they remain understandable, reliable, and trusted by human operators. These systems should support - not replace - the judgement of skilled professionals.

Chapter 5 – Leveraging Emerging Technologies

This chapter illustrates the concrete benefits observed among early adopters of SCM 4.0 technologies, including up to 15% reductions in logistics costs and 35% improvements in inventory performance. The results confirm the added value of AI and automation tools, especially when they are integrated thoughtfully into broader organisational strategies and skills ecosystems.

Chapter 6 – Impact on SMEs

Most SMEs remain at early stages of SCM 4.0 adoption. While many see the relevance of digital tools - particularly in forecasting and planning - they face barriers such as high investment costs, skills gaps, and unclear ROI. Additionally, environmental considerations, though increasingly acknowledged, are often disconnected from digital strategies.

Chapter 6.5.1 is particularly interesting, as it highlights that **trust, transparency, and information sharing** are not only technical issues but **human and cultural challenges**. Building collaborative supply chains requires mutual confidence between suppliers, partners, and customers. The **human dimension** - including leadership, change management, and ethical values - emerges as a cornerstone of successful SCM transformation. Digitalisation alone is not sufficient: social capital must also be nurtured.

Chapter 7 – Impact on VET and Training Centres

VET systems are under pressure to evolve in response to Industry 4.0 and sustainability transitions. New job roles and skill profiles are emerging that require continuous updates to curricula and pedagogical approaches. Strengthening collaboration between industry and training providers is crucial to reducing skills mismatches and ensuring that education supports innovation.

Chapter 8 – SCM 4.0 and the Green Transition

SCM 4.0 is a powerful lever for achieving sustainability goals. By enabling emissions tracking, circular logistics, and resource efficiency, digital tools make it possible to align environmental responsibility with economic performance. Firms that integrate digital and green strategies will be better positioned to meet stakeholder expectations, attract ESG-conscious investors, and contribute to climate objectives.

Chapter 9 – Expert Perspectives

Experts across multiple countries provided overall positive feedback on the report, acknowledging its relevance and value for both industry and training centres. However, they noted that the structure could be clarified in places to improve readability and coherence.

Suggestions were made to deepen the focus on SMEs, integrate more visual case studies, and further explore the social implications of digital SCM. They also recommend to include the purchasing function within the scope of analysis, given its strategic role in both digital transformation and sustainable supply chain practices. This addition would enhance the report's operational relevance and better reflect the full range of SCM activities.

Cross-Cutting Key Insights

- **Digital transformation and specially Artificial Intelligence (AI) is accelerating and is poised to play a determining role in reshaping SCM practices**. It supports greater agility, forecasting accuracy, and decision-making across the supply chain.
- **SMEs face persistent barriers** to adoption and need tailored support.
- **The workforce must be equipped with hybrid skills**, combining data, systems thinking, and sustainability literacy.
- **VET systems require structural adaptation**, with more agile, modular, and industry-aligned content.
- **Sustainability introduces complexity**, but also long-term strategic value.
- **Trust and human relationships** remain central to the functioning of intelligent, interconnected supply chains.

Final Outlook

To unlock the full potential of SCM 4.0, Europe must adopt a coordinated and inclusive approach that places equal emphasis on **technology, people, and sustainability**. This includes:

- Investing in upskilling and lifelong learning.
- Strengthening SME support mechanisms and digital-readiness frameworks.
- Encouraging trust-based collaboration across supply chains.
- Embedding sustainability into all dimensions of SCM strategy and education.
- Modernising training systems and embracing hybrid learning formats.

SCM 4.0 is not just a technical or environmental evolution - it is a systemic transformation of how companies operate, learn, and collaborate. Building the **next generation of ethical, resilient, and human-centred supply chains** will require shared vision, political will, and collective action.

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14. ANNEX

14.1. ANNEX 1 - TARGET AUDIENCE OF SURVEYS

Table 12. Target Audience of Surveys

COUNTRY	TARGET AUDIENCE	Distribution list
GER	SME	Dr.-Ing. Max Schlötter GmbH & Co. KG
		Gotic
		Weisser SPK
		Weisser SPK
		FYSAM
		BurgerSchlozAutomobile
		BurgerSchlozAutomobile
		Huber Automotive
		Schuma
		Stahlbau Süssen
		Cellcentric
		bardusch GmbH & Co. KG
		Kunststofftechnik W.Schneider GmbH
		Häcker Küchen GmbH
		Schlötter
		EWS
		Kollmar
		H. von Wirth
		Bosig
		Strassacker
		Index
		Hartmann
		Steiff
		Edelmann Group
		Bruno Weisser
		Schlagwerk
		Kurfess
		Laubholz
		Mink Bürsten
		Stark Walzen
		Esband
		Esband
		Authenried Kunststofftechnik
		Märklin
		robatherm

		IPM Automotive GmbH
		kühnplast GmbH + Co. KG Kunststoffwerk
		OSG
		Heidelberger Druckmaschinen
	VET	Albert-Einstein-Schule Ettlingen
		Berufliche Schule Rottenburg
		Berufliche Schulen Oberndorf-Sulz (Standort Oberndorf)
		Berufliche Schulen Schramberg
		Carl-Benz-Schule Karlsruhe
		Elektronikschule Tettnang
		Erwin Teufel Schule
		Ferdinand-von Steinbeis-Schule Reutlingen
		Ferdinand-von-Steinbeis-Schule Tuttlingen
		Geschwister-Scholl-Schule Leutkirch
		Gewerbeschule Villingen-Schwenningen
		Gewerbliche Schule Ehingen
		Gewerbliche Schule Geislingen
		Gewerbliche Schule Göppingen
		Gewerbliche Schule Künzelsau
		Gewerbliche Schule Schwäbisch Gmünd
		Gewerbliche Schule Schwäbisch Hall
		Gewerbliche Schule Tauberbischofsheim
		Gewerbliche Schule Tübingen
		Gewerbliche Schulen Donaueschingen
		Hans-Thoma-Schule Titisee-Neustadt
		Hohentwiel-Gewerbeschule Singen
		Humpis-Schule
		Karl-Arnold-Schule Biberach
		Philipp-Matthäus-Hahn Schule
		Richard-Fehrenbach-Gewerbeschule
		Robert-Bosch-Schule Ulm
		Staatliche Feintechnikschule mit Technischem Gymnasium
		Zeppelin-Gewerbeschule Konstanz
		RP Stuttgart
		RP Stuttgart
FR	VET	IUT Rodez BUT QLIO
		In&MA
		CMQ Transport Lézignan
		Lycée Galiéni BTS GTLA
		BUT MLT
		CNAM
		Campus PromoTrans
		Montpellier Business school
		IMT Albi Master
		IMT Mines Alès
		IMT Atlantique MOST

		IUT Limousin
	Expert	Ministère éducation
		Efficairn
		CETIM
		CETIM
		3DS
		TBS Education Supply Chain
		Strategie Excellence
	SME	2PS PROJECTION PLASMA SYSTEME
		A.E.M.
		vauleon
		ACC
		ACMETO SAS
		Acti Group ALMERAS
		AD INDUSTRIE
		ACTIMETAL INDUSTRIE
		Ad'Up
		AEC Aveyron Elec Concept
		AGROPACK
		ALBAGNAC
		ALEA
		ALPHA MECA
		ATS Laser groupe Tournié
		AVANTIS concept
		AVANTIS MANUFACTURING SN R2 MECA
		AVEYMECANIC
		LISI AERROSPACE BLANC AERO
		BODYCOTE
		BOURREL JEAN MARIE (groupe VAULEON)
		BROWN EUROPE
		CASEM 19
		CEMIP
		CHEZE RVC / SEP
		CFM 46
		CHASSINT Peintures
		CLAUX ET FILS ET CIE
		CTM CORREZE TECHNIQUES MECANIQUE
		DEBITEX
		DEFI 12 SAS
		DIACE groupe FMH
		EP3E
		AUTEC / EUROFABRICATION / EUROPE SERVICE
		eXcent
		FEM techno
		FGD
		FIGEAC AERO

		FIN'TECH INDUSTRIE
		FIVES CINETIC
		FIVES MACHINING
		FM2i
		FONDERIE FRAYSSE
		GELY SERGE SARL
		Groupe EUCLIDE SOLUTIONS COREMO BARRIERE
		Groupe EUCLIDE CARE LAM LES ATELIERS MODERNES
		Groupe EUCLIDE MECANAT
		GUDEL SUMER
		HUGON SARL
		I3D CONCEPT
		J P M
		LABROUSSE CAROSSERIE
		LACOTTE INDUSTRIE
		LASER SERVICES France
		LAVAYSSIERE Ets MAVENTIS MAVIPAL
		LF MECA
		LM Industrie
		M-TECKS EAC
		ERCOME Industrie Metal Formage
		M2C
		MATIERE
		MAVENTIS
		MECABRIVE INDUSTRIES SAS
		MECAFFÜT
		MECALLIANCE
		MECATEP
		META GROUPE FMH
		METRASUR INDUSTRIE
		MICHEL PIOCH SA
		MORAN
		MOUNEYRAC
		MP USICAP
		MPRO
		MTI (Mécanique et Travaux Industriels)
		NEXTER MECHANICs
		NIMROD
		META LASER ex OXYMETAL GROUPE MH
		PAGES MECANIQUE
		PATTYN BAKERY DIVISION DE LA BALLINA INDUSTRIES
		PIVAUDRAN
		PLASTIQ CONCEPT
		PLC PROCESS
		POLYLASE
		POTEZ COMPOSITES AEROFONCTIONS SAS

		POUDREX
		RAPIC
		PRECITOL
		RATIER FIGEAC COLLINS
		groupe CHALLENGES
		RECTIF 46 SARL
		RCI
		RGI France
		ROBERT BOSCH SAS
		SAMPEC
		SANZ SAS
		SERMATI SAS
		SERRE
		SNAM
		SOCIETE TECHNIC SERVICES
		SOLEV
		SOTIMECO
		SOUD HYDRO
		Sud DECOUPE INDUSTRIE
		SUD OUEST SYSTEME
		SUD RECTIF MECA
		TEGMA : FRECHIN
		TEGMA : LRD
		TEGMA Finimétaux
		THIOT INGENIERIE
		Usinage 46
		UVGERMI
		VADERE
		VAULEON INDUSTRIES et MURAT
		VM BUILDING SOLUTIONS UMICORE
		VPM automation
		WHYLOT
		Aero XV YMCA Services Cahors ALTARIVA
		ZAJAC MECANIQUE
		Aerospace valley
IT	SME	ROLD
	VET	Istituto Torricelli
SI	SME	MIEL d.o.o.
		GZS
		LTH Castings
		Danfoss Trata
		FANUC
		Hisense Gorenje
		Robeta
		TGK

		Grammer Automotive Slovenija
		Kopa d.d.
		Inea
	VET	MIC Škofja Loka
		ŠC Kranj
		Erudio
		ŠC Novo mesto
		ŠC Nova Gorica
		ŠC Ptuj
		ŠC Ljubljana
		B&B
		ŠC Velenje
		ŠC Ravne
		ŠC Celje
		TŠC Maribor
		ŠC Postojna
		Academia
		IC Geoss
TR	VET	Körfez Mesleki ve Teknik Anadolu Lisesi
		Sabancı MTAL
		Mehmet Tuğrul Tekbulut Mesleki ve Teknik Anadolu Lisesi
		Gebkim Vet
		Denizyıldızları Mesleki ve Teknik Anadolu Lisesi
		İTÜ Mesleki ve Teknik Anadolu Lisesi
	SME	ONBİRON ENDÜSTRİYEL KİMYASALLAR SAN. VE TİC. A.Ş.
		PİROMET PİROMET. MAL. REF. MAK. SAN. VE TİC. A.Ş.
		CFN KİMYA SAN. VE DIŞ TİCARET A.Ş.
		TN MALEIK PETROKİMYA A.Ş.
		GENTAŞ KİMYA SAN. VE DIŞ. TİCARET A.Ş.
		FOSROC CONSCTRACTION
		İZEL KİMYA
		Türk Henkel Kimya Sanayi ve Ticaret A.Ş
		GEBTEK GEBKİM TEKNOLOJİ GELİŞTİRME MERKEZİ

14.1. ANNEX 2 - EXAMPLES OF TRAINING COURSES RELATED TO SCM

Table 13. Examples of Training Courses related to SCM

Country	Training	Training course description and skills	EQF Level	Source
France	University Diploma in Logistics and Transport Management	Logistics, transport, eco-responsibility, sustainability, digital transition, flow management	6	https://www.francecompetences.fr/recherche/rncp/36646/
France	Professional Qualification Certificate: Technicien Logistique Industrielle	Information flow management, industrial consistency, supply and distribution supervision, computerized systems	6	https://www.francecompetences.fr/recherche/rncp/39949/
France	Bachelor's Degree in Technology: Management de la logistique et des transports, spécialité Mobilité et supply chain durables	IT security, sustainability, innovative logistics and transport strategies	6	https://www.francecompetences.fr/recherche/rncp/35391/
France	Bachelor's Degree in Technology: Logistics and Transport Management, Sustainable Mobility and Supply Chain Specialization	Innovative technologies, digital solutions in logistics and transport	6	https://www.francecompetences.fr/recherche/rncp/35390/
France	Bachelor's Degree in Science and Engineering, Intelligent and Connected Systems Maintenance Specialization	Digital and energy transition, AI, mechatronics, predictive maintenance, CMMS (Computerised Maintenance Management Systems)	6	https://www.francecompetences.fr/recherche/rncp/38710/
France	Professional Bachelor’s Degree in Logistics and Flow Management	Warehouse automation, sustainable logistics, cybersecurity, CSR (Corporate Social Responsibility), flow management	6	https://www.francecompetences.fr/recherche/rncp/40064/
France	Bachelor's Degree in Technology: Quality, Industrial Logistics, and Organisation, Supply Chain & Organisation Specialization	Digital tools, IT security, information flow management, supply chain, process optimization	6	https://www.francecompetences.fr/recherche/rncp/35351/
France	Bachelor’s Degree in Science and Engineering - Information Systems	Eco-responsibility, circular economy, data management and analysis, AI, digitization	6	https://www.francecompetences.fr/recherche/rncp/39709/
France	Bachelor’s Degree in Science and Engineering - Computer Science and Digital Systems	AI, Deep Learning, Computer Vision, NLP, databases, digital transformation	6	https://www.francecompetences.fr/recherche/rncp/38732/

France	AI and Data Science Developer	AI development, Data Science, process optimization, predictive maintenance, digital marketing	6	https://www.francecompetences.fr/recherche/rncp/36581/
France	IT Project Coordinator (cloud infrastructures, applications, or data)	Information security, cloud computing, automation, AI, cybersecurity, data protection	6	https://www.francecompetences.fr/recherche/rncp/38478/
France	Data Science Developer and Designer	Predictive analysis, AI, big data, machine learning, data processing	6	https://www.francecompetences.fr/recherche/rncp/35288/
France	Project Manager in Blockchain Solutions	Blockchain, cryptography, Solidity, blockchain application development, smart contracts	6	https://www.francecompetences.fr/recherche/rncp/40146/
France	Designer Integrator of Internet of Things (IoT) Solutions	IoT, automation, connected device networks, data processing, process optimization	6	https://www.francecompetences.fr/recherche/rncp/39237/
France	IT Infrastructure and Security Technician	Networks, cybersecurity, cloud, infrastructure supervision, IT incident management	5	https://www.francecompetences.fr/recherche/rncp/39620/
France	Diploma of Scientific and Technical University Studies: Webmaster et métiers de l'internet	Web development, connected objects, virtual reality, augmented reality, digital content creation	5	https://www.francecompetences.fr/recherche/rncp/36052/
France	**Vocational Degree in Design and Improvement of Industrial Processes and Procedures**	Digital transition, production line, maintenance, robotics, digital tools, cybersecurity, ethics, environmental responsibility.	6	https://maforpro-occitanie.fr/nos-formations/licence-professionnelle-sciences-technologies-sante-mention-metiers-de-l-industrie-conception-et-amelioration-de-processus-et-procedes-industriels-parcours-process-de-fabrication-0
France	**Vocational Baccalaureate in Logistics**	Reception, storage, order preparation, shipment, forklift operation, road transport, safety, quality, environmental regulations, logistics companies, distribution platforms, corporate logistics services.	4	https://joseph-gallieni.mon-ent-occitanie.fr/nos-formations/bac-pro-logistique--29113.htm
France	**Operational Supply Chain Manager Certification**	Logistics management, negotiation, supply chain, transportation, storage, supply, planning, dispatcher, shipping manager	6	https://www.meformerenregion.fr/diplomes/responsable-operationnel-de-la-chaine-logistique#formations-associees
Slovenia	**Mechatronics Technician**	Mechanical engineering, electrical engineering, computer science, automation and robotics	4	School for Service Activities and Logistics, Celje School Centre (www. sdl.sc-celje.si) Secondary Vocational and Technical School Bežigrad, Ljubljana
Slovenia	**Logistics Technician**	Logistics, warehousing, and supply chain management	4	Secondary School for Service Activities and Logistics, Celje

				School Centre (www. sdl.sc-celje.si) Secondary Vocational and Technical School Bežigrad, Ljubljana
Slovenia	**Logistics Engineer**	Logistics, supply chain management, and process optimization	5	Higher Vocational School, Ljubljana School Centre (visjasola.sclj.si)
Slovenia	**Mechatronics Engineer**	Automation, robotics, and the integration of advanced technologies into production processes.	5	Higher Vocational School, Novo mesto School Centre (www.sc-nm.si) L.I.V.E Maribor (prometna.net) ERUDIO Higher Vocational School, Ljubljana (erudio.si)
Turkey	Bachelor's Degree in Logistics	Supply chain management, inventory control, distribution, logistics information systems	6	Istanbul University - AUZEF
Turkey	Associate Degree in Logistics	Storage, transportation, customs procedures, inventory management	5	Istanbul University - AUZEF
Turkey	Vocational High School Program in Logistics	Shipment, warehousing, storage, logistics software, internships, warehouse supervisor, shipment staff	4	Ministry of National Education - Vocational and Technical Anatolian High Schools
Germany	Supply Chain Management	Supply chain management, cost optimization, customer satisfaction, SCOR modeling	5 & 6	https://www.haufe-akademie.de/7867
Germany	Sustainability in Supply Chain Management	Regulations, social and ecological sustainability, sustainable optimization strategies	5 & 6	https://www.haufe-akademie.de/34087
Germany	Strategic Supply Chain Management	Planning and managing logistics networks, cost reduction, simulation and strategic planning	6	https://www.haufe-akademie.de/5357
Germany	Certified Supply Chain Manager	Value chain optimization, cost reduction, logistics project management	6	https://www.haufe-akademie.de/2222
Germany	Certified Supply Chain Manager course	Optimization of value chains, cost reduction, customer-oriented processes, supply chain management fundamentals, project management, practical tools.	6	https://www.haufe-akademie.de/2222
Germany	Certified SAP User in Production Planning	SAP system navigation, master data management, production orders, material movements, inventory management, integration with SAP modules (materials management, sales), reporting tools, capacity/resource management	4 to 6	https://berger-bildungsinstitut.de/bildungsangebote/beruflich/sap-kurse/sap-anwenderkurse/zertifizierter-sap-anwender-produktionsplanung-sap
Germany	Effective work preparation – planning and control of the production process	Order scheduling optimization, production control, material management, ERP/MES systems, capacity planning, lot sizing, IT planning tools, delivery service improvement.	4 to 6	https://www.tae.de/weiterbildung/fertigung-produktion-automatisierung/arbeitsvorbereitung-planung-logistik/effektive-arbeitsvorbereitung-planung-und-steuerung-der-produktion/?dep=89
Italy	Supply Chain, logistics and operations	Supply Chain skills, Logistics flow optimization, Inventory management, ERP, Blockchain, RFID, IoT, Automation, Robotics, AI, Machine Learning, Data analysis, Strategic decision-making, Risk management	6	https://www.24orebs.com/formazione/professional-master/master-supply-chain-logistica-e-operations

Italy	Supply Chain Management	Procurement management, collaborative practices, order-to-delivery, demand-to-supply processes, business partner integration, efficiency, effectiveness, and responsiveness	5	https://www.liucbs.it/catalogo/la-gestione-della-supply-chain/
Italy	Supply Chain Management	Material procurement, production management, product distribution, end-to-end supply chain management, corporate governance models	4	https://www.cegos.it/corsi-formazione/operations/supply-chain-management

14.2. ANNEX 3 - SCM REPORT QUOTATION FROM EXPERTS

Table 14. Result of the SCM Report quotation from experts

Chapter	Question	Average on a score of 4
Overall	Does the report seem useful, relevant, and reliable to you?	3,50
1	Is the purpose of the report clearly explained?	3,43
1	Does the methodology allow you to understand the different steps?	3,29
2	Is the definition of SCM clear and relevant to you?	3,43
2	Is the scope of the report and the different levels of SCM clearly presented?	3,57
3	Is the current SCM context, including economic, geopolitical and climate challenges clearly explained?	3,71
3	Are the current SCM software and AI market trends clearly explained?	3,86
4	Are the impacts of Digital Technologies 4.0 (Edge VS Cloud-based computing, AI, IoT, Cybersecurity & Blockchain etc.) on SCM clearly described?	3,71
4	Are the benefits, challenges, and limits of each technology clearly illustrated in relation to their impact on SCM transformation?	3,57
5	Is the integration of AI technologies across SCM processes (PP, S&OP, MPS, MRP, FCS/ICS) clearly described and illustrated?	3,29
5	Are the benefits, limitations, and future trends of AI adoption in SCM clearly presented?	3,29
5	Is the Control Tower case a relevant and interesting example to illustrate IA-driven expected improvements?	3,00
6	Are the internal barriers to SME digital adoption (finance, tech, skills) clearly explained?	3,57
6	Is the impact of digitalisation on SME organisation and workforce transformation clearly illustrated?	3,57
6	Evaluation of Companies Survey: It seems useful and pertinent to you	3,14
6	Evaluation of Companies Survey: The questions seem pertinent to you	3,57
6	Evaluation of Companies Survey: The results are clearly explained and described	3,71
6	Evaluation of Companies Survey: The results can be considered reliable	3,29
6	Evaluation of Companies Survey: The sample seem representative to you	2,71
6	Do you find the future perspectives, recommendations, and conclusion of this chapter useful?	3,86
7	Does this chapter provide relevant examples to better understand the current state of SCM training and related fields?	3,43
7	Does this chapter provide useful insights into the challenges and opportunities for training centres in the adoption of technology 4.0?	3,57

7	Does this chapter clearly explain the impact of emerging technologies on the skills taught in SCM education and related fields?:	3,43
7	Does the explanation of the impact of 4.0 technologies on pedagogical methods seem interesting and relevant to you for this report?	3,14
7	Evaluation of the VET Centres Survey: It seems useful and pertinent to you?	3,29
7	Evaluation of the VET Centres Survey: The questions seem pertinent to you	3,57
7	Evaluation of the VET Centres Survey: The results are clearly explained and described	3,71
7	Evaluation of the VET Centres Survey: The results can be considered reliable	3,43
7	Evaluation of the VET Centres Survey: The sample seem representative to you	3,43
8	Does this chapter help you understand how SCM 4.0 technologies can drive sustainability and green transformation in supply chains?	3,43
10	Does this chapter effectively summarize the key findings on the ecological and digital transformation of SCM and SCM training?	4,00

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