STRENGTHENING SUPPLY CHAINS: STRATEGIES FOR RESILIENCE AND AGILITY

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LOGISTICS AND SUPPLY CHAINS THROUGH THE GAME

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In today's dynamic world, logistics and supply chains are key to the functioning of society and the economy. Games and simulations offer an interactive approach and allow participants to explore and develop logistics concepts and solutions for improvement. Focused on overcoming key logistics challenges, these games encourage innovation and waste recognition. In the context of supply chains, the games show the complex connections between different nodes and the challenges that arise due to potential disruptions. Among the popular games we can find the Beer distribution game, Paper or lego airplane game, Scum ball Game or Marshmallow Challenge. Through the tekst, we find that games and simulations are a valuable tool for researching and improving logistics and supply chains and greatly contribute to a better understanding of the key processes of the modern way of life.

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1 Introduction

Logistics, defined as the process of planning, organising, managing, and controlling the flow of resources (materials, people, information, energy, capital, and knowledge), plays a vital role in modern life. By systematically managing these flows, value is added to the final product or service, satisfying end-users and enhancing organizational efficiency and success. In essence, logistics directs the movement of the key components that support both business operations and consumer experiences.

The importance of logistics can be seen in three key aspects. First, consider its value relative to gross domestic product (GDP). According to Statista (2023), the global logistics industry—one of the backbones of international trade—was worth over €8.4 trillion. In 2020, global logistics costs rose to $9 trillion, accounting for 10.7% of the world's GDP ($85.24 trillion that year).

Efficient logistics management is crucial for reducing costs associated with transportation, warehousing, inventory control, and other critical areas. Optimizing these processes enables companies to cut expenses, allocate resources more effectively, and gain a competitive market edge.

The second aspect of logistics' importance lies in its role in creating value. By reducing costs and providing high-quality services that overcome the constraints of time and space, logistics has a direct influence on customer satisfaction. Enhancing the user experience through timely and efficient deliveries, accurate order fulfillment, and reliable after-sales services demonstrates the value that logistics brings to both businesses and consumers.

The third aspect is logistics' central role in enabling a wide range of economic activities. It forms the backbone of global trade by facilitating the movement of raw materials, intermediate goods, and final products across regions. As Waters (2003) states: nothing is produced, no material is moved, no operation is performed, no product is delivered, and no customer is served without logistics.

Given the significant impact of logistics on the economy and daily life, understanding its principles is essential. Individuals with logistics knowledge can manage the flow and connections within supply chains more effectively, reduce costs, and improve operational efficiency. Additionally, studying logistics develops critical problem-solving skills and the ability to navigate complex logistics challenges, making professionals valuable across various industries.

An increasingly effective way to learn about logistics and supply chains—which are closely interconnected —is through games and simulations. These methods offer an interactive approach, allowing learners to engage with simulated logistics scenarios and gain a stronger grasp of theoretical concepts. Participating in logistics-based games fosters critical thinking, decision-making skills, and a deeper understanding of the complexities of logistics processes. This better learners for the dynamic and demanding logistics environments of the real world.

The following sections explore the key features of logistics and supply chains and highlight the importance of integrating games and simulations into logistics education. Several specific examples of games used to better understand logistics concepts and their practical applications are also presented.

2 What is Logistics

As stated in the introduction, logistics is the process of managing the flow of resources in a way that adds value to the final product—satisfying the end user—and enhances the efficiency and success of an organization. Its crucial role in the modern world has already been highlighted; we will now summarize its key tasks and objectives.

2.1 Core Function

To better understand the importance of logistics in both the global context and our daily lives, it is essential to highlight its core function. Logistics is most commonly defined as the function that bridges the gap between supply and demand. These gaps can be categorized as spatial, temporal, quantity, diversity, and information gaps.

– The **spatial gap** refers to the physical distance between suppliers of resources and the end users.

- The **temporal gap** occurs when there is a time difference between the availability of a resource (product or service) and the customer's need or desire to use it.
- The **quantity gap** arises when there is a mismatch between the quantity available and the quantity desired by the customer.
- The **diversity gap** occurs when customers expect a greater variety of products than what is currently offered—either from a single supplier or across multiple providers.
- The **information gap** reflects the difference between the information customers seek and the information accessible from the supplier's side, and vice versa.

Addressing these gaps lies at the core of logistics. The essential question is: how can these gaps be bridged as effectively as possible? This leads to the primary goal of logistics—to ensure that the right product, in the right quantity, in the right condition, at the right place, at the right time, for the right customer, at the right cost, and with the right environmental impact is delivered.

But what does "right" actually mean? It is defined by the customer (e.g., buyer, or end user), whose expectations and requirements can vary depending on the context. As such, logistics must be organized in a way that consistently meets or exceeds these expectations, both within the organization and in interactions with external partners.

2.2 Finding Ways to Overcome Gaps – The 8 Wastes in Logistics

Further exploration of logistics reveals that processes must be executed in a way that consistently meets—or exceeds—customer expectations. This is achieved by creating value from the customer's perspective, primarily through overcoming the previously mentioned gaps and eliminating the inefficiencies or "wastes" in the process.

A commonly referenced concept in this context is the eight wastes in logistics, derived from the Kaizen philosophy, which emphasizes continuous improvement and the elimination of non-value-adding activities. These eight wastes are:

1. **Overproduction** – Producing or stocking more than is needed can be financially and operationally inefficient.
2. **Excessive movement and handling** – Unnecessary movement during transport and storage wastes time and energy.
3. **Waiting** – Delays caused by waiting for materials, products, or information reduce overall efficiency.
4. **Unnecessary transportation** – Extra transport increases costs and prolongs delivery times.
5. **Over-processing** – Unneeded or overly complex processes consume time and resources.
6. **Underutilized human potential** – Failing to use employees' knowledge, skills, and abilities may limit the organization's performance.
7. **Errors and defects** – Mistakes, rework, and defective products waste both time and materials.
8. **Overproduction** – Repeated deliberately because it often leads to or exacerbates other forms of waste.

Identifying and eliminating these wastes is key to improving logistics performance, reducing costs, enhancing quality, and increasing customer satisfaction.

3 Logistics and Supply Chains

When we talk about logistics, we cannot overlook the concept of the supply chain. The two are closely linked with the supply chain representing a broader perspective in which logistics plays a central role. The main focus of the supply chain concept is on interconnection, collaboration, trust, and the coordinated functioning of all participants within the chain.

A supply chain (SC) is a complete network of entities—both directly and indirectly involved—that work together to serve the same customer or end user. It begins with raw materials and ends with the final customer who uses the product, linking numerous companies along the way (CSCMP, 2025).

The structure of the supply chain includes key flows that connect different stakeholders through various processes and functions, all the way to the end-user. These flows begin with the initial supplier and continue through to final delivery to the customer. Importantly, the final user is considered an integral part of the supply chain.

The main flows that form a supply chain are:

- Material and service flow – This mostly runs from suppliers to producers, distributors, and retailers, and finally to end customers. A reverse flow includes product returns, servicing, and disposal of waste.
- Information flow – supports the transmission of orders and coordination of the material flow. It also ensures product traceability.
- Financial flow – flows in the opposite direction to the product flow and ensures payment settlement for goods and services exchanged between supply chain members.
- Knowledge flow – usually flows both ways, such as in the exchange of experience or collaborative research and development.

These flows move between individual actors (also referred to as nodes, entities, or tiers) connected with the purpose of fulfilling the needs of the end-user. Key actors in the supply chain include:

- end customer (consumer);
- retailer;
- distributor or wholesaler;
- manufacturer;
- supplier.

The supply chain can be further extended to include service providers, which encompass a wide range of companies offering services related to the supply chain. These services include transport, warehousing, finance, market research, product development, technology, insurance, public services, sustainability, and reverse logistics. It is important to note that not all tiers are present in every supply chain.

A third critical element of the supply chain is the set of organizational processes that link the various actors into a chain and generate the previously mentioned flows.

Key processes include:

- planning;
- procurement (sourcing);
- production;
- sales and distribution;
- reverse logistics.

4 Role of Games in Understanding Logistics and Supply Chains

Game- and simulation-based learning has gained significant traction across many fields over the past 15 years, including in logistics and supply chain management. This approach involves a variety of so-called *serious games*, which incorporate different methods and media types. Most commonly, these include board games, role-playing games, card games, LEGO-based activities, sports-inspired games, or digital simulations (William et al., 2018).

Games have a strong potential to enhance traditional forms of education (Ruben, 1999). As emphasized by Pacheco-Velazquez et al. (2023), new generations of learners require educators who understand their audience and use diverse teaching methods that actively engage students in the learning process. Similarly, Monaco and Martin ((2007) found that students prefer to play an active role in their learning, while methodologies based solely on one-way information transfer are neither enjoyable nor creative.

Workshops and lectures that incorporate game-based activities provide participants with instant feedback and freedom to explore the subject matter, as pointed out by Vanany & Syamil (2016).

A growing body of literature emphasizes the benefits of using games in education (Hou, 2015; Pacheco-Velazquez idr., 2023; William idr., 2018). These include:

- encouraging active or action-based learning;
- enhancing learning and understanding of complex content;
- increasing engagement, motivation, and problem-solving capabilities;

- improving decision-making skills and fostering the development of social competencies;
- promoting better understanding and learning scientific concepts.

Games offer hands-on experience, requiring players to plan strategies, apply knowledge and skills in a simulated environment, and respond to the consequences of their decisions. This approach helps learners more easily translate theoretical knowledge into practical applications.

The added value of using games in education is also evident in the field of logistics and supply chains.

Games support active learning, enhance understanding of complex logistics concepts, and boost engagement, motivation, and problem-solving skills, all of which are critical in the fast-paced logistics environment.

Moreover, games help players grasp the intricate interconnections within supply chains, as they develop strategies, make decisions, and adapt to outcomes in simulated environments. A wide variety of games, tailored to different generations and levels of prior knowledge, creates numerous possibilities for effectively integrating game-based learning into educational settings.

In the next section, we will explore specific examples of games that can be used in various educational contexts.

5 Game Examples

5.1 The Beer Distribution Game

The Beer Distribution Game simulates material and information flows within a production–distribution system. Its purpose is to demonstrate supply chain management principles and the bullwhip effect—a phenomenon related to the transmission of information as it moves along the supply chain. Developed in the 1960s at MIT, this is one of the most well-known logistics games. It was originally designed to help students, managers, and executives visualize the challenges of managing dynamic systems–in this case, a supply chain delivering beer from a brewery to the final customer.

The game's core objective is to explore human behavior in managing supply chains, emphasize the importance of information sharing, and demonstrate how distribution operates in a supply network ((Mitraa, 2020). Initially created to explain system dynamics, it has since become a widely used tool for illustrating the functioning of supply chains. It is most commonly used to:

- demonstrate the bullwhip effect;
- show how individual parts of the system influence each other;
- highlight the differences between individual and systemic thinking:
- illustrate optimization strategies and the value of information systems.

What makes the game so interesting and useful is that, although the supply chain structure and rules are simple, the resulting behavior is highly complex. The Beer Game is also well documented in the literature (Grasl, 2015).

The goal of the game is to minimize the total costs of the supply chain. The standard version involves four players: a retailer, wholesaler, distributor, and beer producer. Customer demand originates at the retail level, which is restocked from the wholesaler, who orders from the distributor, who in turn orders from the producer. Each period, players decide how much to order, and the brewery decides how much to produce.

There are lead times for both production and shipping. While materials move from production toward the customer, information flows in the opposite direction. Delays occur between placing an order and the supplier receiving it—both in terms of order processing and information flow.

The game can be played in about 90 minutes, with a minimum of four players, though it is possible to run multiple groups simultaneously (see Figure 1.1).

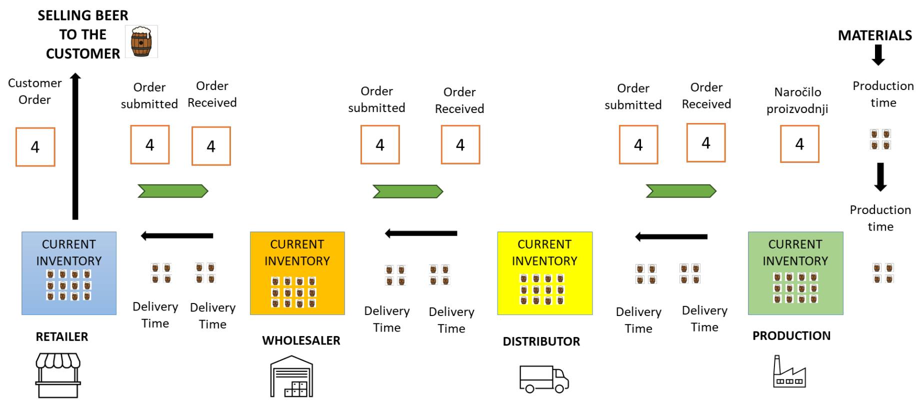

Figure 1.1: Beer Game playing board

Source: own source

5.2 The Ball Game

The Ball Game focuses on improving processes that address spatial and temporal gaps–two of the fundamental challenges in logistics. It encourages lean and agile process design, with an emphasis on waste elimination and continuous improvement, in line with the Kaizen philosophy.

Skills and tools developed through this game include:

- communication;
- continuous improvement;
- flow;
- PDCA (Plan, Do, Check, Act);
- SCRUM approach;
- teamwork;
- the eight types of waste in logistics.

This game can simulate almost any process–from transport and warehousing to customer service. The ball represents a task, and its movement represents the transfer of responsibility between team members.

Goal: Pass as many balls as possible from point A through the team and back to point A in two minutes. Alternatively, participants can measure how long it takes to process a set number of balls. Common props include tennis balls, ping pong balls, or lightweight plastic balls.

The game can be played by a single group or multiple teams.

Adding a storyline enhances engagement. For example, the team produces magic spheres, which only gain their magic after being touched by each person in the team. If two people touch the ball at the same time, the magic is lost. Additionally, magnetic forces prevent team members from passing the ball directly to their immediate neighbor. The person who starts/ends the process represents the customer, who wants the magic added to the balls. This narrative makes the rules more understandable and the activity more enjoyable (see Figure 1.2).

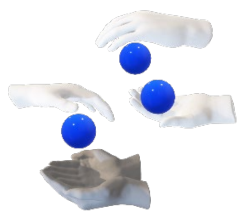

Figure 1.2: The Ball Game
Source: own.

The game can be tailored to different audiences: primary school students, high school students, university students, or organizational teams. Adaptations should reflect the group's age and prior knowledge of logistics, supply chains, or lean processes, with explanations adjusted accordingly.

5.3 Building an Airplane

This game involves assembling an airplane using either paper or LEGO bricks.
One version of the game includes four workstations with uneven task distributions, intentionally creating a bottleneck (e.g., at station three).

Both approaches explore lean production concepts, focusing on push vs. pull systems, as well as flow time, cycle time, quality, workload distribution, and the identification of logistical waste.

The objectives include demonstrating how lean methods reduce waste–especially through minimizing inter-stage inventory and lead time–by applying techniques such as pull production, Kanban, bottleneck analysis, cycle time optimization, line balancing, and observing worker behavior in operational settings.

One version of the game includes four workstations with uneven task distributions, intentionally creating a bottleneck (e.g., at station three).

The simulation progresses through several steps.

- Step 1: Each participant builds an airplane individually.
- Step 2: Tasks are assigned to workstations; this illustrates the push process, where each person works as long as there is material, without considering inventory buildup.
- Step 3: The process is redesigned so that only one airplane is built at a time, reducing inventory and lead time and highlighting the benefits of lean and Kanban.

You can make the game more engaging by introducing airplanes of different colors to simulate changing customer demand. Adding a quality control step further enriches the simulation.

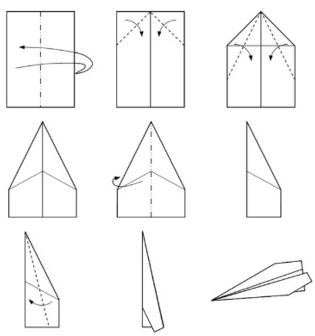

Figure 1.3: Example of paper airplane production
Source: (Čerin, 2013)

The game typically takes 20 to 90 minutes and requires at least four players (see Figure 1.3).

5.4 LEGO Construction Game

The LEGO Construction Game simulates logistics processes within a supply chain. illustrating the challenges of overcoming spatial and temporal gaps. The goal of the game is to reconstruct an object identical to the one specified by the customer, using various supply chain actors.

The game can be played in several variations. In one version a participant takes on the role of customer needs researcher, who observes a pre-built LEGO structure (representing the customer's requirement) and communicates its composition down the chain. Other participants assume roles such as retailer, wholesaler, distributor, manufacturer, or supplier–or even internal business roles like salesperson, designer, producer, or warehouse manager.

Through this game, players can explore disruptions and communication breakdowns that commonly occur within the supply chain.

5.5 The Marshmallow Challenge

The well-known Marshmallow Challenge tasks players with building the tallest possible free-standing structure in 18 minutes using spaghetti, tape, string, and a marshmallow, which must be placed on top.

This game encourages:

- out-of-the-box thinking;
- teamwork;
- the PDCA approach;
- problem-solving under constraints;
- group communication and leadership dynamics;
- collaboration, innovation, and strategic planning.

It teaches a lean mindset for managing risks and shows the value of continuous experimentation to reduce waste (see Figure 1.4).

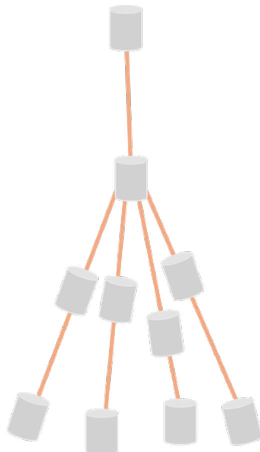

Figure 1.4: The Marshmallow and Spaghetti Tower Game
Source: own.

5.6 Paper Chain Game

This game focuses on how teamwork and organization affect the final outcome of a process. It emphasizes reducing process time (temporal gaps), improving information flow (informational gaps), meeting customer needs, and minimizing waste in logistics. Participants work together to create a chain of paper rings, learning how collaboration impacts process efficiency.

5.7 Walking Across the Galaxy

In this game, players use paper plates to cross a designated space from point A to point B, simulating the challenge of overcoming spatial gaps.

Rules:

- Players may only step on the paper plates.
- If no one is standing on a plate, it "flies off into space."

– At first, each player receives a certain number of plates (e.g., three), but this number is gradually reduced over time—simulating supply chain disruptions.

The game can be adapted to suit different age groups and learning levels.

5.8 5S Method Simulation

This word game simulates the 5S method, commonly used to design highly organized work environments. Players use number-based tasks to experience the five stages of 5S and learn how the method supports continuous improvement in logistics and operations (see Figure 1.5).

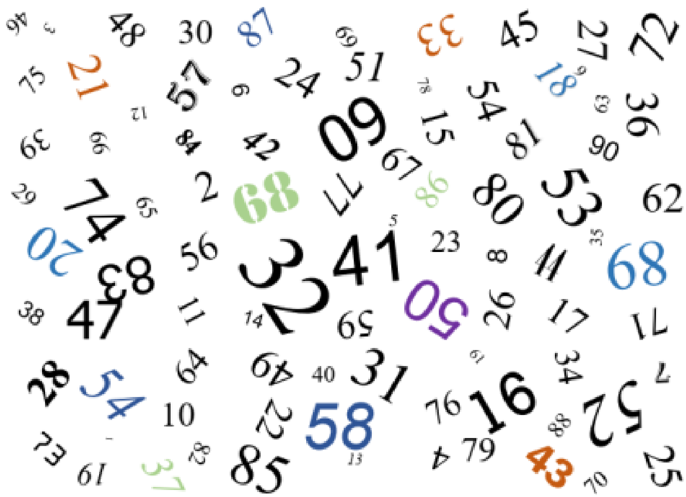

Figure 5.5: 5S Method Simulation Game
Source: own source

5.9 Drawing a Pig or Fish

This game demonstrates the importance of process standardization and the pursuit of continuous improvement, which are core principles in lean logistics. The objective is to draw a standardized pig or fish. Each participant receives a sheet with a grid and written or oral instructions on how to draw the standard figure. The game illustrates how clear standards and instructions influence process outcomes (shown in Figure 1.6).

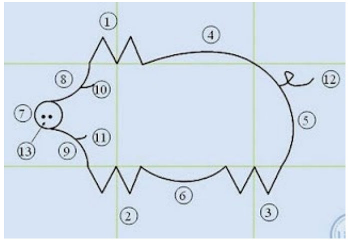

Figure 1.6: Standard Pig Game
Source: (Standard Pig, n. d.)

These are just a few examples of the many games available to explore logistics and supply chains. Literature offers a wide variety of similar games that, in addition to being fun, provide practical learning opportunities to improve efficiency in logistics and supply chains.

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How to Increase Strategic Supply Chain Resilience in 5 Steps

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Recognizing that the reliability of the supply on the global market has been risky for some time has become an undeniable fac in times of disruptions. Big international supply chain players have been dealing with this issues for over a decade. If we want our supply chain to be resilient, we must be aware that to enhance resilience, we need to forecast potential disruptions and develop scenarios how to manage them. For flexible and resilient supply chain it is crucial to have clearly defined supply chain strategy based on a) Risk analysis; b) Value chain analysis and c) Maturity model and benchmarking. This helps us to identify priority measures and to develop an action plan to achieve greater resilience and adaptability, which are becoming foundation of business in the 5.0 society.

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1 Introduction

A supply chain (SC) encompasses the lifecycle processes defined as involving physical, information, financial, and knowledge flows whose purpose is to satisfy end-user requirements with products and services from multiple linked suppliers (Ayers, 2000). In line with this definition, the supply chain consists of supply, production, transportation, distribution, and product and service sales processes. It involves all stakeholders who are directly or indirectly involved in fulfilling customer demands (Chopra & Meindl, 2007). A supply chain is thus defined as a network of three or more organizations or individuals directly involved in the flows of products, services, finances, and/or information from the origin to the customer (Mentzer et al., 2001). A typical SC also represents a network of materials, information, and services that defines connections with the characteristics of supply, transformation, and demand (Chen & Paulraj, 2004). If we want our supply chain to be resilient, we must first acknowledge that increasing resilience requires anticipating potential disruptions and creating scenarios for how to manage them. But why don't all companies do this? Simply because it is not that easy, as a resilience strategy must involve various SC stakeholders, not just a single company.

Certain authors point out that the lifecycle can refer to both the market lifecycle and the usage lifecycle, which differ for durable goods and services. This distinction makes after-sales service an important component of the SC.

The SC can vary in complexity depending on the number of members and the diversity of business processes, but it usually has a central role and manages the entire supply process. According to Mentzer et al. (2001), three levels of SC complexity can be identified:

- Direct SC – composed of the focal company, its suppliers, and its customers.
- Extended SC – includes, in addition, the suppliers' suppliers and the customers' customers.
- Ultimate SC – encompasses all companies involved in all flows of products, services, finances, and information from the original suppliers to the final customers, as well as functional intermediaries such as third-party logistics providers (3PL).

Supply chain management (SCM) represents a fundamental and integral part of business operations. It can improve customer service and satisfaction, reduce operating costs, and simultaneously improve the company's financial performance (Orozco-Romero et al., 2020). SCM therefore plays a key role not only in logistics but in the broader economy (Liu et al., 2022). Adapting the SC has become a necessity, but for most companies, this remains a challenge due to the lack of real-time data availability and limited responsiveness of planning systems (Marmolejo-Saucedo et al., 2020). The continuous improvement of SCM systems has driven the development of various digital tools for business process automation (Marmolejo-Saucedo et al., 2020) As a result, supply chains are shifting from traditional hierarchical structures toward *value networks*, characterized by complex, interconnected, and interdependent relationships (Kajba et al., 2023). Therefore, knowledge flows, learning, and collaboration are gaining importance, in some cases even rivalling more established flows such as product movement, control, and coordination (Kalaboukas et al., 2021).

2 Phases of Supply Chain Management

The supply chain management process consists of five phases (see Figure 2.1):

1. SC strategy,
2. demand and SC planning,
3. sourcing and procurement,
4. production,
5. logistics and distribution.

Figure 2.1: Phases of the SC management process
Source: own source

To increase resilience to disruptions and ensure a flexible SC, it is essential for a company to first have a clearly defined supply chain strategy. For this reason, we will focus primarily on this phase.

2.1 Phase 1: Supply Chain Strategy[1]

2.1.1 Key steps and activities

Defining a robust SC strategy is typically a three- to six-month project and is often outsourced to a consulting company to avoid conflicts of interest. However, a company can also carry out this process internally by following the five steps below (see Figure 2.2):

1. Understand the current (existing) state.
2. Collect best practices and performance metrics.
3. Develop the desired future state.
4. Perform a gap analysis between the desired and existing state.
5. Create a plan to bridge the gap between the desired future and current state.

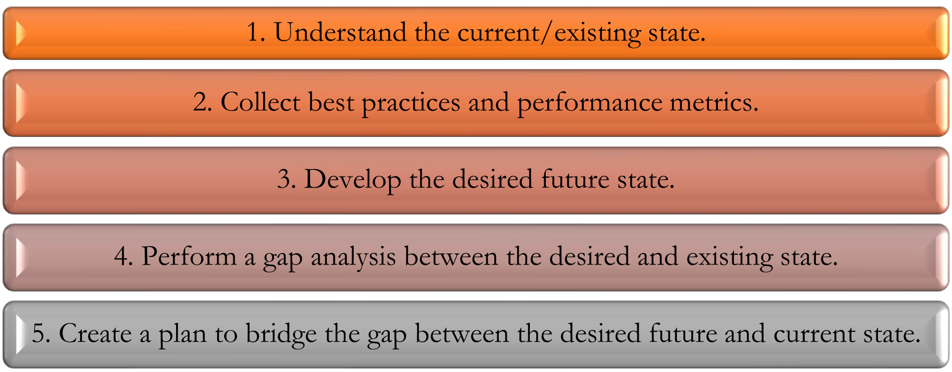

Figure 2.2: Key steps of SC strategy

Source: own source

The following section presents each step in more detail through their activities:

1. Understand the current/existing state:

– Define key data to be collected.
– Design and prepare questionnaires.

[1] Adapted from Obrecht, n.d.

- Select key stakeholders to be interviewed.
- Conduct interviews.
- Process collected data/information, typically using information technology (IT).
- Study, understand, and document the current state.
- Validate the current state with the company.

2. Collect best practices and performance metrics:

- Define relevant metrics and best practices to be collected.
- Select and analyze appropriate metrics, assess the maturity level of the company, and identify best practices.
- Interview experts and gain an understanding of the specific industry.

3. Develop the future state:

- Develop a SC management maturity model.
- Evaluate the company's SC management maturity.
- Define the desired future state based on:
  - the current state,
  - collected performance metrics and best practices,
  - SC maturity level of the company,
  - strategic vision of the company.

4. Perform a gap analysis between the desired future and existing state:

- Compare the existing and desired future states.
- Identify possible initiatives required to transition from the current to the future state.

5. Create a plan to bridge the gap between the desired future and current state:

- Utilize all possible initiatives identified in the previous step, including:
  - An explanation of how each initiative will help reach the target state,
  - a cost-benefit analysis,
  - prioritization of initiatives,

– development of a plan including priorities and a clear timeline,
– effective implementation of initiatives,
– tracking and measuring progress.

Some steps may be implemented by the organization with minimal effort, while others require more energy. The identification and analysis of potential risks–i.e., possible disruptions that could jeopardize SC operations–are of utmost importance.

Awareness that global supply reliability has long been at risk became undeniable during extraordinary events such as the coronavirus pandemic. Major international supply chain players have been dealing with unreliable deliveries for over a decade. Similar supply chain disruptions have already occurred during previous pandemics (e.g., SARS, Ebola, etc.), nuclear disasters (e.g., Fukushima), natural catastrophes (e.g., Balkan floods, Asian tsunamis, U.S. hurricanes, etc.), military conflicts (e.g., the Middle East, Syria, Somali pirates, Ukraine, etc.), trade wars and international diplomacy (e.g., China's economic expansion restrictions, the Iranian embargo...), and so-called revolutions like the Arab Spring. However, disruptions have never before affected so many countries on various continents simultaneously, impacting entire networks of competitors. Rethinking future business models that more actively incorporate supply disruptions and allow for more proactive intervention is increasingly relevant.

The focus and severity of business changes largely depend on the duration of disruptions and the perceived risk of recurrence. If a disruption is short-term (an "optimistic scenario"), organizations sometimes forget it too quickly and eventually become less cautious again. For example, they may once again equip their products with cheap global components of questionable origin, produced in uncertain working conditions and without insight into environmental impacts across the SC. If a crisis or disruption is long-lasting, responsible companies can be expected to place more emphasis on evaluating the origin of raw materials and their suppliers–not necessarily for environmental sustainability, but to increase supply security and resilience.

More and more global players are seeking alternative suppliers in geographically diverse regions, theoretically minimizing the chance of simultaneous supply outages. However, in the procurement world, this is still not a given–many EU companies do not even know who or where their primary material suppliers are, let alone understand the extraction conditions or potential supply risks.

Recently, there has also been a trend toward nearshoring–choosing suppliers located nearby, which enables shorter transportation routes and greater responsiveness in emergency situations. This, in turn, can present an opportunity for long-term value creation, revitalization of EU-based manufacturing, and increasing perceived product value in the eyes of the end customer. Additionally, in the euro area there are no currency risks, labor laws are better regulated, and social factors are considered (e.g., practically no child or forced labor), and we observe higher levels of quality control. On the other hand, this represents a major shift–de-globalization of business operations, and potential drivers of global instability, as unfortunately, nothing connects us more than money.

3 Tips and Recommendations for Increasing Supply Chain Resilience

3.1 RiskAssessment and Mitigation

To properly assess corporate or project risks, it is important to use the following dimensions:

- Probability – how likely it is that the risk will occur.
- Impact – what the potential effect of the risk is on business operations or the functioning of the organization.

To evaluate the probability of a risk, a probability scale can be used, which should also visually depict the levels of probability (see Table 3.1).

Table 3.1: Defining the Probability Scale

Probability Scale	Definition
Almost certain	More than 90% chance of occurrence.
Likely	Between 60% and 90% chance of occurrence.
Possible	Between 20% and 60% chance of occurrence.
Unlikely	Between 5% and 20% chance of occurrence.
Rare	Less than 5% chance of occurrence.

Source: own source

For assessing the potential impact of a risk, a scale is also used that visually illustrates the levels of impact (shown in Table 3.2).

Table 3.2: Defining the Impact Scale

Impact Scale	Definition
Extreme	The risk will cause project failure or business collapse.
Major	The risk will significantly affect the success of the project or company.
Moderate	The risk may affect the success of the project or company.
Minor	Almost no effect on the success of the project or company.
Negligible	No effect on the success of the project or company.

Source: own source

The risk value for the examined organization is calculated by multiplying the probability dimension by the impact dimension. If the resulting risk is high and its impact on the organization is significant, the company must prepare for it and develop a response scenario to address the potential disruption or risk. Organizations that prepare in advance emerge as winners during times of disruption, whereas those that do not anticipate potential future scenarios usually take too long to adapt or are unable to adapt at all—which can result in loss of market position or even business failure.

Table 3.3: Value Calculation

Probability		Impact		Value
What is the probability of the risk occurring?	×	What is the potential impact of the risk	=	The risk matrix helps to easily calculate the risk value.

Source: own source

Based on the calculation and the information on the **risk value** for each individual risk in a project or company, **priority actions** are determined. These actions help to assess **how important it is to address and prepare for a given risk** (see Tables 3.3 and 3.4).

Table 3.4: Defining the Risk Value Scale

Risk value	**Definition**
Very High	Risks that must be treated as **priority no. 1**.
High	Risks that must be treated as **priority no. 2**.
Medium	Risks that must be treated as **priority no. 3**.
Low	Risks that must be treated as **priority no. 4**.
Very Low	Risks that must be treated as **priority no. 5**.

Source: own source

The steps to be followed to determine the risk value are:

Step 1: List all identified risks in a table (or a more extensive Excel spreadsheet) titled "Risk Register Template" (Table 3.5).

Step 2: Assign the risks to the Risk Matrix Template (Tables 3.6 and 3.7).

Table 3.5: Risk Register Template (Example of a Partially Completed Template)

Risk No.	Risk Name	Risk Description	Probability	Impact
1	Slower website performance	Improving the resolution of our images will increase their size, which may slow down page loading time.	Likely	Major
2	New competitor entering the market	[Enter risk description]	[Enter text]	[Enter text]
3	[Enter risk name]	[Enter risk description]	[Enter text]	[Enter text]
4	[Enter risk name]	[Enter risk description]	[Enter text]	[Enter text]
5	[Enter risk name]	[Enter risk description]	[Enter text]	[Enter text]
6	[Enter risk name]	[Enter risk description]	[Enter text]	[Enter text]
7	[Enter risk name]	[Enter risk description]	[Enter text]	[Enter text]

Source: own source

Table 3.6: Risk Matrix Template 3 × 3 (Example Template)

Probability				
	Likely	– *Enter project name* – *Enter project name* – *Enter project name*	– *Enter project name*	– *Enter project name*
	Possible	– *Enter project name*		– *Enter project name*
	Unlikely		– *Enter project name*	*Enter project name*
		Minor	**Moderate**	**Major**
		Impact		

Explanation:

Risk treatment priority level #3	Risk treatment priority level #2	Risk treatment priority level #1

Source: own source

Table 3.7: Risk Matrix Template 5 × 5 (Example Template)

Probability		Impact: Extreme	Impact: Major	Impact: Moderate	Impact: Minor	Impact: Negligible
	Almost certain	– *Enter project name*	– *Enter project name*			– *Enter project name*
	Likely	– *Enter project name*				– *Enter project name*
	Possible	– *Enter project name*	– *Enter project name*	– *Enter project name*	– *Enter project name*	
	Unlikely					
	Rare				– *Enter project name*	

Explanation:

Risk treatment priority level #5	Risk treatment priority level #4	Risk treatment priority level #3	Risk treatment priority level #2	Risk treatment priority level #1

Source: own source

3.2 Best Practices and Examples

Table 3.8 presents examples of companies and scenarios outlining what actions to take in response to specific risks.

Table 3.8: Examples of Risks and Mitigation Measures

Risk	Mitigation Measures
1. HIGH SUPPLY RISK FOR COMPONENTS (e.g., supplier in Ukraine, China)	1. Search for alternative supplier(s). 2. Conclude contracts with existing suppliers to cover disruptions. 3. Prepare a list of substitutes.
2. UNRELIABLE SUPPLIER	4. Supplier evaluation (delivery time, costs, % fulfillment, reliability, flexibility).

Risk	Mitigation Measures
3. HIGH ELECTRICITY/ENERGY PRICES (e.g., why does a surge in gas prices affect electricity prices?)	5. Long-term contracts. 6. Investment in self-sufficiency. 7. Improve energy efficiency. 8. Reduce dependence on a single energy source.
4. INTEREST RATE (How does it affect project implementation?)	9. Increase the profitability margin of the project. 10. Secure financing with a fixed interest rate. 11. Finance in local currency. 12. Seek alternative sources of financing.
5. ENVIRONMENTAL RISKS (ESG) (e.g., products containing palm oil)	13. Obtain ISO 14000 certification. 14. Introduce and integrate ESG into strategic management. 15. Sustainability reporting. 16. Carbon footprint calculation. 17. Sustainability development strategy. 18. Avoid high-risk raw materials. 19. Prepare a list of substitutes.

Source: own source

To conduct such an analysis of risks, maturity, competition, and environmental impacts, accurate data is essential. When considering the supply chain (SC) concept and the product life cycle within it, data must be collected in a fundamentally different manner compared to an analysis based solely on internal company data. In this case, data is gathered across all tiers and levels of the supply chain. The desired information flow may also include sensitive business data (e.g., supplier margins), which companies have a legitimate interest in keeping confidential. Therefore, the collaborative component and partnership-based relationships are key.

When studying and monitoring risks, it is important to recognize the problem of the "tail event"—which refers to risks defined as events with an extremely low probability of occurrence but potentially very high impact on business operations, the supply chain, and the economy and society as a whole. A typical example is the COVID-19 pandemic, which affected the global economy and society through previously unimaginable measures, even though the likelihood of a global pandemic was considered close to zero.

3.3 Maturity Model and Competitive Benchmarking

The next step in preparing a strategy to increase supply chain resilience is to develop a supply chain management maturity model, illustrated with the example below (Table 3.9 and Figure 2.3). This model allows an organization to assess which areas are well-developed, where it performs above average, and where it is lagging behind its competitors.

Table 3.9: Example of a Maturity Model

	Basic	Below Average	Average	Advanced	World Class
Procurement Strategy	– There is barely a company-wide procurement strategy. – The procurement strategy has not been communicated. – Procurement is not recognized as a player in resource acquisition. – Supplier negotiations are primarily price-based.		– A company-wide procurement strategy exists, but it is not comprehensive. – Formal communication of the procurement strategy with suppliers and some parts of the organization. – Procurement is recognized as a player in resource acquisition. – Supplier negotiations begin to go beyond price.		– A comprehensive, company-wide procurement strategy exists. – Procurement strategy is formally communicated to suppliers and the entire organization. – Procurement is recognized as a leader in sourcing. – Customer service and cost performance are optimized through close supplier relationships.
Organization and Human Resources	– Procurement is viewed as a support function. • Procurement is tactically focused. • The function is mostly staffed with low-skilled resources. • Career paths are unclear.		• Procurement begins to be seen as a critical organizational function. • Procurement becomes more strategically driven. • The procurement team starts offering incentives to attract top talent with advanced education.		• Procurement has a seat at the table as a valued partner. • Procurement is strategically led. • The team includes highly skilled personnel with advanced education. • Career paths are clearly defined with performance expectations at each level. • Procurement is involved across most areas of company spending.
Procurement Process	• Few or no formal procedures. • Business units make purchases with no specific guidance. • No formal negotiation strategy is defined.		– Documented processes are known and mostly followed by staff – Business unit purchases follow defined guidelines. – Processes are rarely reviewed. – Process ownership is not centralized.		– Formally trained staff are familiar with and follow documented processes. – Business units follow defined and continuously improved guidelines. – Processes are regularly reviewed to ensure the

			application of best practices. – Centralized ownership of procurement processes.
Technology	– No global procurement system is in place. – Systems are manual and labor-intensive – Data is mainly in "paper-based" format.	– A global procurement system exists but is not always user-friendly. – IT procurement solutions have been identified, but most are not yet implemented. – Focus is on transaction automation.	– The global procurement system is intuitive for users. – IT solutions for procurement are identified and implemented. – Focus is on automation of interactions.
Supplier Relationship	– A win-win mindset is increasingly adopted. – Awareness of the need for trust-based relationships. – Cooperation guidelines and goals are defined. – Supplier selection criteria include cost, technology, availability, and flexibility.	– • A win-win mindset is increasingly adopted. • Awareness of the need for trust-based relationships. • Cooperation guidelines and goals are defined. • Supplier selection criteria include cost, technology, availability, and flexibility.	– A win-win mindset is fully embedded. – Collaboration agreements are in place, and benefits are realized. – Strategic alliances exist with suppliers who share risks and opportunities. – Suppliers are treated as a virtual extension of the organization.

Source: own source

As shown in Figure 2.3, it is less worthwhile to invest in "Organization and Human Resources," as we are already above average in this area and significantly outperforming our competitors. However, we are lagging behind in the areas of "Supplier Relationship" and "Technology." Therefore, it is more strategic for the organization to focus on improvements in "Supplier Relationships" and the development and integration of "Technology" into business processes, as this will enhance our resilience and operational capability during disruptions.

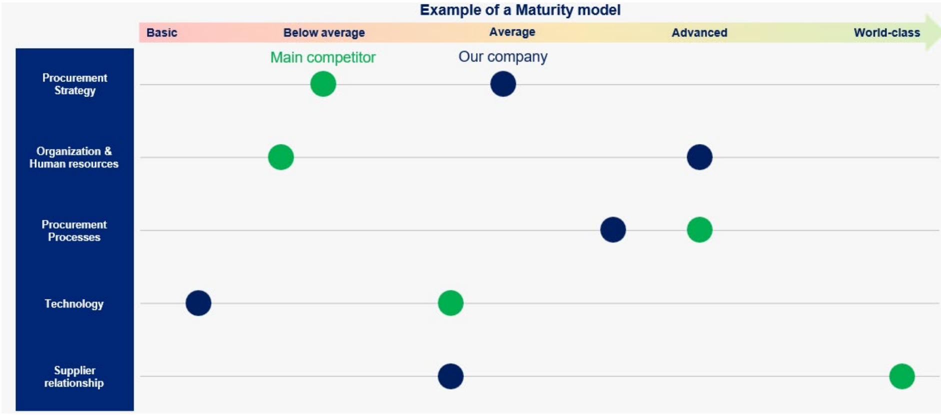

Figure 2.3: Example of a maturity model
Source: own source

3.4 Value Chain Analysis

Within the preparation of a supply chain strategy, attention must also be given to the value chain. The value chain describes the individual components and activities that enable value creation for the customer. If we spread our focus too evenly across all components and activities, we may run out of time, energy, and resources to make improvements in the key areas. It is therefore necessary to first identify the critical value-creating areas and allocate more attention to them than to the remaining, possibly supporting or unnecessary activities. In companies, we often encounter time constraints, which can be effectively resolved by defining the key areas of strategic importance and eliminating those that consume excessive resources without delivering sufficient benefits. The value chain is thus what enables us to generate profit margins (see Figure 2.4).

An example from the dairy industry shows that a major Slovenian dairy processing company discovered that certain products (such as cheese and butter) bring significantly higher added value compared to yogurt. Their butter and cheese are also more well-known, requiring less investment in marketing than yogurt. They found that, given the current demand, they could sell significantly larger quantities of butter and cheese, but they lacked sufficient production capacity. Yogurt, on the other hand, brings lower margins, incurs higher costs, and they do not believe it has strong sales potential.

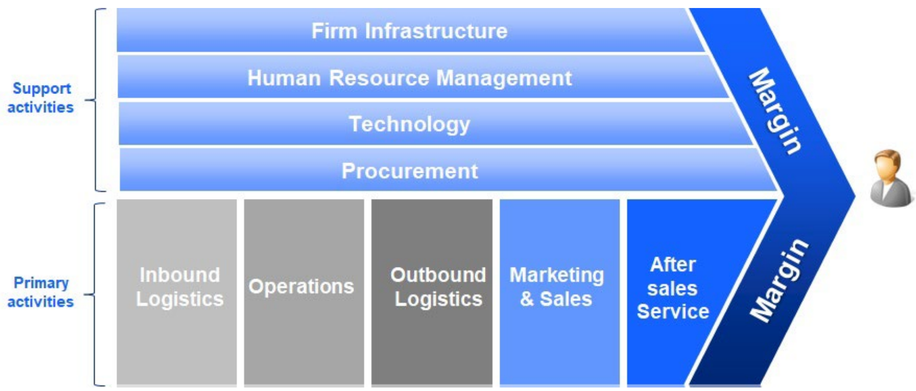

Figure 2.4: Representation of the Value Chain
Source: own source

What should be done in such a case? The company decided to discontinue yogurt production and prioritize cheese and butter. By withdrawing yogurt from production, they freed up capacity for butter and cheese, reduced marketing costs, and increased their profit margins. They were able to do this relatively quickly, as these are similar products that require comparable workforce skills and machinery.

This move optimized their operations, reduced production variability, simplified processes, and achieved higher added value. However, they also reduced their resilience by lowering the diversity of their production. For example, if demand for cheese or butter were to decline, the decision might be questionable. In this particular case, the likelihood of that happening is extremely low, so the decision was bold. Still, if they were producing both traditional and vegan cheese, even with lower added value, it would make sense to continue producing vegan cheese, given the rising trend in plant-based diets. This means that future market conditions must also be taken into account—not just the current ones.

3.5 Assessment of Priority Areas

It is important to create a simple matrix to prioritize all potential initiatives that need to be implemented to transition from the current state to the desired future state. Two criteria used in most prioritization matrices are (Table 3.10):

Table 3.10: Factors Used to Select Priority Activities

Impact	Effort
An initiative with high impact would mean one of the following: – The initiative must occur to achieve the desired future state, – The initiative will significantly reduce costs or increase revenues.	**The "Effort" criterion is assessed based on the following factors:** – Ease of implementation, – Required time frame, – Required resources (number of people, capital investment, etc.).

Source: own source

Focus should be placed on initiatives that have the greatest impact and require the least effort (Tables 3.11 and 3.12).

Table 3.11: Priority matrix

Impact		High effort	Low effort
	High	**Long-term initiatives** (actively strive to reduce the required effort)	**Priority initiatives**
	Low	**Unattractive initiatives** *(do not pursue)*	**Low-value initiatives** *(pursue opportunistically)*
		High	**Low**
		Effort	

Source: own source

Table 3.12: Matrix of Proposed Priority Initiatives

Impact		High effort	Low effort
	High	1. Enter the name of initiative 2. Enter the name of initiative 3. Enter the name of initiative 4. Enter the name of initiative 5. Enter the name of initiative	1. Enter the name of initiative 2. Enter the name of initiative 3. Enter the name of initiative 4. Enter the name of initiative 5. Enter the name of initiative
	Low	1. Enter the name of initiative 2. Enter the name of initiative 3. Enter the name of initiative 4. Enter the name of initiative 5. Enter the name of initiative	1. Enter the name of initiative 2. Enter the name of initiative 3. Enter the name of initiative 4. Enter the name of initiative 5. Enter the name of initiative
		High	**Low**
		Effort	

Source: own source

The availability of accurate and reliable data is essential for conducting comprehensive analyses of risks, maturity, competition, and environmental impacts. When applying the supply chain perspective and considering the product life cycle within it, data collection processes differ substantially from those based solely on a company's internal information. In such cases, data must be gathered across all tiers and at every level of the supply chain. The intended information flow may encompass sensitive business data (e.g., supplier profit margins), which companies have a legitimate interest in protecting. Consequently, fostering effective collaboration and establishing strong partnership relationships is a critical prerequisite for the success of such analyses.

3.6 Development of a Business Case Study

Every project an organization undertakes should be clearly defined in terms of its goals for achieving the desired state of increased supply chain resilience. Some projects within companies are executed at a strategic level, while others are more spontaneous and based on perceived business opportunities. The proportion of each depends largely on the organizational culture and the values the company supports.

Table 3.13: Objective of the Business Case

Objective	Partial objective
The objective of the business case is to complete a thorough analysis of the potential project to facilitate the decision on whether to proceed with it.	Determine whether the project supports the overall business strategy.
	Identify the potential value and value drivers of the project.
The business case is a differential analysis that compares the current state ("as-is") with the target state as the result of the project ("to-be").	Define the costs and expected benefits of the project.
	Determine the time-distributed effect of net cash flow, return on investment (ROI), and the payback period of the project.

Source: own source

Nonetheless, it is important to recognize that some non-strategic projects may offer financial benefits, but they also burden organizational resources, tie up financial capital, and require human capital. If such projects align with the strategic directions and capabilities of the organization, they are certainly welcome. However, if they unintentionally increase exposure to risks and disruptions and negatively impact resilience, it is worth reconsidering whether to proceed with implementation (see Table 3.13).

If the aforementioned dairy processing company identified an opportunity in the vegan cheese market, the project would likely make sense, as it would enhance their resilience, differentiation, supplier and segment diversification, and open access to new customers in a highly trending market. On the other hand, if they decided to develop a low-fat or fruit-flavored yogurt instead of the poorly selling current yogurt, it would be questionable whether that would be worthwhile. Similarly, the dairy company would not engage in selling cars, even if sales figures in 2022 were excellent, because it lacks the necessary expertise, information, and resources–and most importantly, such a venture is not aligned with its strategic direction.

Due to the scarcity and limited availability of resources–whether raw materials, energy, or human capital–companies are increasingly aware that the future well-being of both the organization and society as a whole depends on how successfully they address the challenges of sustainable development today. The economic component can no longer be separated from or in contradiction with the environmental and social components. Rather, through risk analysis, maturity assessments, and identification of priority areas, we can reduce potential harm and focus on business operations that yield the best outcomes environmentally, socially, and economically. As previously mentioned, interdisciplinarity requires strong cooperation throughout the entire supply chain. Transparency, flexibility, and readiness for change are the core characteristics of a resilient supply chain (SC).

4 Disruptions and Resilience in Supply Chains Today and Tomorrow

4.1 Disruptions in Supply Chains Will Become the New Reality – Building Resilient Chains Remains a Major Challenge

Disruptions are a specific combination of various factors in a rapidly changing period. There is no single answer as to what causes supply chain (SC) disruptions, as they are usually a mix of more (e.g., labor shortages, reduced availability due to lower production during COVID lockdowns) or less predictable factors (e.g., international conflicts, pandemics).

Recent reasons for disruptions include the following:

a) Much has been written about the job crisis, tourism, and hospitality industries during COVID, job losses, etc., but we often overlook that the situation is not one-dimensional—it is more about the stratification of the population. On one hand, a portion of the population did lose their jobs and income; on the other hand, a significant part accumulated substantial savings while working from home, with restaurants, tourist facilities, and stores closed. Their income remained the same or even increased, and they are now driving demand and spending more than before COVID. The pandemic also changed people's habits: in the past, we bought more business attire; now, we buy more sportswear—mostly online. We don't go to gyms, but we buy more fitness equipment. Hotels reduced capacity, and part of the workforce moved to other sectors, which means that the level of tourism demand we saw in 2022 and 2023 can unfortunately only be addressed by raised prices. The higher the demand, the higher the price of a product or service—this is basic economics. On the other hand, camping gear and motorhomes have seen unprecedented growth, indicating that demand has shifted even within tourism segments.

b) Manufacturing plants in Asia and Europe operated at reduced capacity from 2020 to 2022 due to decreased demand (in industries such as automotive, white goods, and textiles). This affected the entire SC, as orders for components and parts from manufacturers and suppliers decreased. Consequently, raw material orders also dropped, leading supply chains to function at reduced capacity. When demand returned (e.g., in the automotive industry during the second half of 2022 and the first half of 2023), the rebound was sharp. Given the known bullwhip effect in SCs, it's clear that such global shifts in production and consumption cannot be reversed overnight. In early 2021, companies were still complaining in February and March about tough conditions, low order volumes, reduced demand, and potential layoffs. Then a surge in demand hit, and within two to three months, these same companies couldn't keep up with orders. They increased their procurement of materials, raw inputs, and components. However, returning to the previous state is always more difficult than scaling down, which is financially painful, whereas scaling up presents organizational challenges. When demand returned, companies were cautious at first, didn't overstock, and underestimated planning and forecasting. This led to the so-called bullwhip effect—small fluctuations led to massive impacts at the end of the SC. That's why many companies are now rightly concerned about how to meet demand given current uncertain supplies. Rapid adaptation and planning will become essential even for small and medium-sized enterprises.

c) Price is no longer the only key factor. In 2022, the most important thing was to ensure the delivery of the ordered goods. The importance of partnerships in SCs became evident. In some sectors, component prices changed daily. SC partners now realize that long-term purchasing relationships and cooperation matter more than short-term profit, and relationship-building doesn’t happen overnight. Responsiveness and reliability are reflections of SC relationships. In 2023, with increased corporate caution and uncertainty about future business volumes, building resilient and responsive SCs is no longer optional. We have moved from a buyer-driven market to a supplier-driven one, and now we are returning to a more balanced reality where the buyer again plays a greater role—but now on a more cooperative, partnership-based level.

d) China better anticipated certain long-term risks and future business conditions. It secured raw materials and supplies at much lower prices during a period of low demand, while demand from the EU and U.S. was dormant. China made better use of strategic investments in rare materials, resources, and processing industries abroad (mainly in Africa), while the EU, despite criticizing the double standards of Chinese investments, has been inconsistent in its own investment approach in Africa. As a result, China secured a more resilient and reliable supply of key resources for transport, electrification, and the growth of electronic device production. There are also speculations that one of China’s goals is to flex its economic muscle and position itself as the new leading global economy—even at its own (financial) expense. The same approach applies to Chinese internet giants (e.g., Baidu, Alibaba), which the Chinese Communist Party also regulates under "higher" goals. Resources that supply demand in the EU and U.S. are disrupted due to factory shutdowns, reduced output, and distribution bottlenecks, causing headaches for companies worldwide. A more diversified and geographically closer supplier base—even at slightly higher prices—can significantly reduce exposure to long-term disruptions, but only if it’s part of a pre-planned strategy and not a panic-driven reaction when it’s already too late.

4.2 Ports and Maritime Transport

Disruptions in ports—caused by halted production, followed by increased cargo volumes, labor shortages at ports, and high transportation costs—are not something that can be resolved overnight. Just clearing the backlog of delayed deliveries and orders at Chinese ports and shipping them onward to ports in, for example, the U.S. (with the most well-known case being the Port of Los Angeles, where there was usually one ship anchored, but now dozens of ships are waiting for days to unload) takes several months—even under optimal conditions. Practically all logistical resources are in short supply, from containers to trucks. On the other hand, shipping companies are reporting record profits, yet global freight rates and shipping volumes are already declining. In the meantime, the balance of power has shifted. A logistics service provider that a year ago would have been quickly replaced and held liable for contract penalties due to delays or unfulfilled orders, is now being politely asked to deliver goods at all—otherwise, production could halt (e.g., Audi).

Because of port delays, ships often opt to reroute to another port, which is mostly a matter of business optimization for shipping lines. But when multiple shippers (or vessels) make the same decision, it causes real chaos—some containers are unavailable, some end up in the wrong ports, and others are still on ships headed back to China. In such situations, further optimization of distribution via trucking becomes impossible, creating a domino effect. Chaos is also evident within the ports themselves. Where previously containers were often loaded directly onto trucks with a 3-day wait time, they now get moved two or even three times, manipulated, and wait up to 12 days for an available truck—consuming time, capacity, and delaying the much-needed return to normal operations.

4.3 Solutions on the Horizon

One of the solutions lies in rail transport, which is increasingly being invested in worldwide (in the EU, the Balkans, China), although logistics companies are not yet as accustomed to using it. To some extent, rail transport could, in the long term, provide part of the solution due to its reliability and more stable pricing. For example, in the U.S., certain previously closed rail terminals have already been reactivated.

Last year, much was said about localizing supply chains, finding alternative suppliers, and assessing supplier risk, but as conditions partially normalized this year, there's a risk that companies will too quickly forget these adjustments until the next disruption strikes. The reality is that some component and parts manufacturers no longer exist in Europe—they were moved eastward due to unprofitability, lower costs, and environmental concerns. Rebuilding such production capacity would take time (at least 2–3 years), higher prices compared to Chinese products, and bring new environmental burdens in the EU. This again raises questions: what will the situation be like in 2–3 years? Will demand remain high? Will such an investment pay off?

However, if we don't prepare now, we will be in the same position at the next disruption as we were last year. Even if we succeed in establishing replacement production and significantly shortening supply chains, the problem of material/raw material shortages remains. The cause of this lies not only in increased demand and supply chain disruptions but also in financial speculation and market manipulation. In Q2 and Q3 of 2020, capital flowed into financial markets, mainly stocks and ETFs. By the end of 2020, this momentum slowed, and capital moved into cryptocurrencies. When growth also stalled, the next refuge became raw materials—but not in the traditional form like gold, which is typically a crisis hedge.

Prices soared, some commodities fluctuated wildly (e.g., lumber rose by over 400%, then dropped 150%). Electricity prices surged and then, in summer 2023, we even saw extremely negative electricity prices for the first time. The same happened with natural gas in Croatia. Such volatility is enormous. The underpricing of raw materials over the last decade is one of the overlooked factors—we have driven constant demand growth over the same period, which is fundamentally unsustainable. Other contributing factors include global population growth, rising living standards, especially in developing countries, which means that raw material exporters are increasingly becoming importers themselves. For example, oil from South Africa. We're all fighting over the same limited resources.

The circular economy and bioeconomy are EU priorities not just for sustainability reasons but for pragmatic ones. The EU must focus even more on circularity, efficient material use, and transitioning to a bioeconomy. The reason isn't just the well-known push for sustainable development and EU leadership in fighting climate change, but also the practical limitation of resources and the region's vulnerability. The EU is not rich in strategic raw materials and has repeatedly been caught off guard by shocks (e.g., the oil crisis in the 1970s, supply chain interruptions in the automotive industry after the Fukushima disaster, dependence on Russian gas...). We did not learn enough from those events. Building more resilient and adaptive supply chains, which will form the foundation of a reliable future supply, must therefore be based primarily on accessible resources and a diversified supplier network.

Notes

Adapted from (Obrecht, n. d.). Some tables and figures are adapted from lectures of Obrecht from slides which themselves were derived from insights based on Deloitte, BCG & McKinsey Consultants.

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DESIGNING PROCUREMENT STRATEGIES FOR GREATER SC RESILIENCE

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Disruption in modern supply chains is inevitable, so increasing the resilience of organizations is crucial. Strategic procurement, especially through the Kraljic matrix, is key to greater resilience. This model classifies procurement sources into four main groups: strategic, leveraged, bottlenecks and non-critical products, each of which requires a specific approach. It should be understood that the factors affecting the rating in this matrix are not always equally important and have different values. Designing procurement strategies based on this matrix is a complex dynamic process that enables organizations to better adapt to changing conditions and needs. The Kraljic matrix is a valuable tool for managing disruptions in supply chains, as it helps organizations increase resilience and stability. Procurement strategies based on this model are an effective approach for successful operations in an unpredictable business environment.

Keywords:
disruptions,
resilience,
procurement,
procurement strategies,
Kraljic matrix

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1 Introduction

We live in an era of increasing global interconnectedness and interdependence. The complexity of these worldwide connections is greater than ever before in history. Consequently, major disruptions in one part of the world's economic environment can quickly ripple across regions, disrupting the links between economic entities and shaping our daily lives.

Many of these disruptions manifest through supply chains–or more accurately, networks–that experience interruptions in the flow of goods, services, finances, and information among individual chain links. The interdependence of supply chain elements exposes the vulnerabilities of companies and organizations that are heavily interconnected and reliant on external partnerships. Modern business models such as Just-in-Time (JIT) have only intensified the impact of these disruptions (ShakirUllah et al., 2014).

The consequences of such disruptions are diverse, including delivery delays, resource shortages, increased costs, reduced productivity, and damage to a company's reputation. These effects impede the normal functioning of organizations, especially supply chains, and thus necessitate adaptations and changes to traditional strategies.

Disruptions–particularly on the supply side–have clearly demonstrated the need to rethink conventional approaches. This has led to increased research focused on how companies can adopt resilient and flexible practices to mitigate the impacts of sudden and unforeseen events (Yi et al., 2011).

Supply chain resilience is essential for managing disruptions. The growing complexity and interconnectivity of supply chains have led to greater vulnerability, prompting a surge in research on the topic. Gartner (2021) emphasizes the need for supply chains to become more resilient and adaptable. However, most companies acknowledge that their supply chains were originally designed for cost efficiency rather than resilience.

Resilience is defined as the ability of a system or community to withstand and recover from unexpected events. In the context of supply chains, it refers to the adaptive capacity to prepare for, respond to, and recover from disruptions. It is also a critical component of risk management and ensuring business continuity (Resilience | UNDRR, 2007).

Given the rising number of disruptions in upstream supply chains, which often result in more significant and far-reaching consequences, it is important to highlight that upstream resilience (on the supply side) focuses on the company's procurement function. This includes developing capabilities to anticipate, adapt to, respond to, recover from, and learn from disruptive events through effective resource management (Brusset & Teller, 2017; Pereira et al., 2020). Roberta Pereira (2014) stresses that procurement, in this context, acts as a vital link between the organization and its supply-side environment, playing not only a reactive but also a proactive role. She further argues that companies must adjust their procurement functions and strategies to respond swiftly to disruptions, as these are vital in building resilient supply chains.

1.1 Procurement Strategies

The Dictionary of the Standard Slovene Language (*Slovar slovenskega knjižnega jezika,* 2014) defines a strategy as a procedure or method for achieving a goal. Within this context, a procurement strategy can be defined as a process or method for achieving procurement objectives. It consists of a set of decisions related to how resources are acquired.

According to Freytag and Mikkelsen (2007), procurement strategies for sourcing resources have become more important than ever. Their goal is to create a mechanism for linking suppliers with buyers. The use of procurement strategies reduces risks stemming from various factors while enhancing the effectiveness of procurement activities. Furthermore, the application of procurement strategies reduces a company's exposure to opportunistic behavior by other companies and increases the likelihood of successful collaborative relationships (Chen et al., 2004).

Hesping and Schiele (2015) conducted a literature review on the development of procurement strategies and explain that forming a single, general strategy for the procurement function is a difficult task. Instead, various approaches have emerged, the most commonly used being: category management, purchasing portfolio models, strategic sourcing, global sourcing, or supply base management.

Purchasing portfolio models are considered one of the most common approaches to developing procurement strategies (Caniëls & Gelderman, 2005). There are various models, most of which are based on the first model developed in the 1980s by Kraljic (Kraljic, 1983).

2 Kraljic's Purchasing Portfolio Model

The Kraljic purchasing portfolio model–also known as the Kraljic Matrix–is widely regarded as the most frequently applied framework for formulating procurement strategies based on a portfolio approach to sourcing . It has become the benchmark for other portfolio-based models (Ghanbarizadeh et al., 2019a) and plays a key role in classifying suppliers and developing procurement strategies to mitigate supply risks and increase organizational resilience (Bhusiri et al., 2021). The model significantly influenced the evolution of strategic procurement within companies (Caniëls & Gelderman, 2005; Gelderman, 2003) and has inspired numerous authors to conduct further research into portfolio models (e.g., Caniëls & Gelderman, 2007a; C.J. Gelderman & Weele, 2002; Olsen & Ellram, 1997a).

At the core of Kraljic's Matrix lies the principle that procurement managers–faced with suppliers of varying strategic importance–must tailor their strategies to the specific characteristics of their procurement markets (van Weele, 2018). By doing so, companies can protect themselves against harmful supply disruptions and better manage constant technological developments and economic growth (Caniëls & Gelderman, 2005).

Kraljič emphasized that a company's need for a procurement strategy depends on two factors (Kraljič, 1983; Montgomery et al., 2018; Ghanbarizadeh et al., 2019b; Tip et al., 2022):

(1) the **impact on profit** or the strategic importance of procurement, and

(2) **procurement risk** or the complexity of the procurement market. Procurement risk is assessed based on supply shortages, the rate of technological and/or material substitution, entry barriers, logistics costs, or the complexity and conditions of monopolistic or oligopolistic markets.

Procurement sources can be classified within a four-quadrant matrix based on two key dimensions (Figure 3.1). The quadrants are as follows:

- Non-critical items (low risk and low profit impact)
- Bottleneck items (high risk and low profit impact)
- Strategic items (high risk and high profit impact)
- Leverage items (low risk and high profit impact)

Each quadrant represents a specific category of products, services, or suppliers reflecting different interests for the company. By assessing their position using relevant criteria, decision-makers can determine the most appropriate procurement strategies and actions to leverage their purchasing power against key suppliers and reduce their risks to an acceptable minimum (Bhusiri et al., 2021; Olsen & Ellram, 1997b).

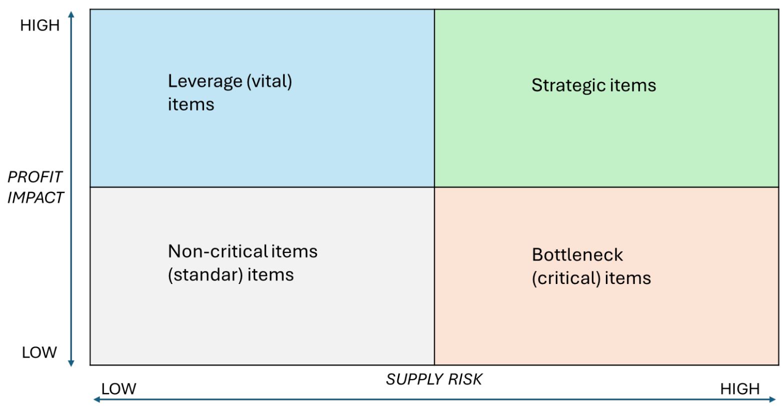

Figure 3.1: Classification of Procurement Products According to Two Dimensions
Source: adapted from Kraljič (1983)

According to van Weele (2018), many procurement managers tend to simplify their assessment of supply risk by relying primarily on thenumber of potential suppliers as the main criterion. However, in practice, a wide range of criteria should be considered to to gain a more accurate and nuanced understanding of this aspect. Over time, these criteria have evolved, shaped by the specific characteristics of individual companies and their procurement strategies. Some of the most important criteria, as summarized by van Weele (2018), are illustrated in Table 3.1.

Table 3.1: Criteria for the Two Dimensions of the Kraljic Matrix

Impact on Profit	Supply risk
– Volume in comparison to total purchase volume – Share of procurement products in total cost price – Contribution of procurement products to the company's total margin – Potential for cost savings through: competitive bidding or volume agreements – Price elasticity – Discount and bonus schemes	– Branded vs. standardized products – Patented or licensed products – Availability of substitutes – Specific quality and logistics requirements (e.g., JIT) – Extent to which the company's customers require certain suppliers – Supplier's share in the buyer's total purchase volume – Buyer's share in the supplier's total sales revenue – Market structure: free competition vs. monopoly – Market conditions: supply-demand ratio – Political stability; (market) regulation, and other political conditions – Supplier's production capacity utilization – Supplier's financial position – Switching costs for changing suppliers

Source: adapted from: (van Weele, 2018).

The next section (Figure 3.2) presents the distinguishing characteristics of each product group.

Importance of procurement (impact on profits) **Criteria:** material cost/total cost, value added profile, profitability profile, etc.	High	Material management		Supply management	
		Leverage items: (electric motors, fuel oil, hardware, electronic equipment,..)	**Timeframe:** Various, usually from 12 to 24 months	**Strategic products:** (rare metals, high-value components)	**Timeframe:** Up to 10 years, regulated with long-term strategic impact (combination of risk and contracts)
		Key performance criteria: Cost/Price and Material Flow Management	**Product type items:** Mix of Different Goods and Specific Materials **Product availability:** Large	**Key performance criteria:** Long-term availability	**Type of purchasing products:** Rare and/or high-value products **Product availability:** Natural scarcity and rarity
		Typical purchasing items: Multiple suppliers, mainly local	**Decision-making body:** Mainly decentralized procurement	**Typical purchasing items:** Established global suppliers	**Decision-making body:** Centralized procurement
		Procurement management		Resource management	
		Non-critical products: (iron, coal, office supplies)	**Timeframe:** Restricted, usually 12 months and less	**Bottlenecks:** (electronic components, external services)	**Timeframe:** Variable, depending on availability vs. short-term swap option
		Key performance criteria: Functional and operational efficiency	**Type of Purchasing products:** Mixture of Different Goods and Specific Materials **Product availability:** Large	**Key performance criteria:** Cost control and reliable short-term care	**Type of purchasing products:** Predominantly specific products **Product availability:** Rarity based on production
	Low	**Typical purchasing sources:** Established local suppliers	**Decision-making body:** Decentralised	**Typical purchasing sources:** Global, mostly new suppliers with new technology	**Decision-making body:** Decentralized procurement and centrally coordinated
		Low			High
	Complexity of the purchasing market (purchasing risk) **Criteria:** supply quantity, monopoly or oligopolistic conditions, speed of technological progress, entry barriers, logistical costs and complexity, etc.				

Figure 3.2: Kraljic Matrix – Characteristics of Individual Groups of Purchasing Items

Source: adapted from: (Kraljič, 1983)

2.1 Procurement Market Analysis

Once procurement products have been classified within the matrix, the next step involves analyzing the procurement market, with a particular focus on balance of power between the buying company and its suppliers. At this stage, the company evaluates its purchasing power. A systematic analysis of the procurement market is conducted to assess the availability of strategic materials in terms of both quality and quantity, as well as the relative strength of existing suppliers. In parallel, the company analyzes its internal requirements and supply channels to determine its capacity to negotiate favorable procurement conditions.

Potential evaluation criteria include: the market size relative to supplier capacity, the company's market share in comparison to competitors, the availability of substitute products on the market, the feasibility of in-house production, and similar factors (C. J. Gelderman & Mac Donald, 2008).

2.2 Strategic Positioning

After analyzing the market, where the company evaluates the bargaining power of suppliers relative to its own, it positions strategic items within the purchasing portfolio matrix (Figure 3.3). Based on this relative power position, the company may adopt an **aggressive strategy** ("exploitation" – situations where the buyer has greater bargaining power), a **defensive strategy** ("diversification" – when suppliers dominate and hold greater bargaining power), or a **well-balanced strategy** ("balance" – in cases of mutual power symmetry) (Apostolova et al., 2015).

High			
Power on the side of the customer (company)	Exploitation	Exploitation	Balancing actions
	Exploitation	Balancing actions	Diversification
Low	Balancing actions	Diversification	Diversification
	Low Power on the side of the seller (supplier)		High

Figure 3.3: Strategic Positioning

Source: Adapted from: (Kraljič, 1983)

In buyer-dominant situations, the purchasing organization exerts greater control over product requirements than the supplier. This is common in the automotive industry, where supplier–buyer relationships are often asymmetrical. Buyers dictate specifications and conditions, and suppliers are expected to comply. In contrast, in supplier-dominant markets, the roles are reversed. Leveraging advanced technology and sophisticated marketing strategies, suppliers can effectively "lock in" their customer. This is frequently seen in the business information technology sector, where IT providers make customers fully dependent on them for hardware, software, and services (e.g., SAP, Oracle, Microsoft). Customers buy their hardware and software from a single supplier, only to discover that the same supplier charges high prices. Usually, service guarantees are valid only if all products and services are purchased from the same provider. The customer has very limited leverage and must accept the terms set by the supplier. Outsourcing can easily lead to such a situation (van Weele, 2018; van Weele & Rozemeijer, 2022). In balanced relationships, neither party dominates. Instead, both have a mutual interest in maintaining a stable relationship, which can develop into a genuine partnership.

3 Designing Procurement Strategies

Based on the characteristics of the individual product groups in the Kraljic Matrix, proposed procurement activities, and the power balance between suppliers and buyers, various authors have suggested tailored procurement strategies for each product group. Van Weele (2018), for example, proposes four basic procurement strategies, summarized in Table 2.2, which indicates the corresponding matrix quadrants and the key objectives for each strategy. These strategies align with the procurement actions discussed earlier for each product group (quadrants and product groups).

Although strategic recommendations for Kraljic Matrix items are often limited to a single strategy per quadrant, empirical research into its practical application by purchasing managers (Caniëls & Gelderman, 2007b; C. J. Gelderman & Van Weele, 2003, 2005) suggests greater nuance. Specifically, somestrategies aim to (1) maintain the current position within the quadrant, while others are focused on (2) shifting to a different position. Figure 2.4 presents an overview of the strategic orientations associated with each of the four quadrants or product categories. A total of nine procurement strategies are illustrated. While some are aimed at transitioning out of a quadrant, others focus on remaining within the current one.

Table 3.2: Four General Procurement Strategies

	Partnerships	Competitive Bidding	Supply Assurance	Category Management and E-Procurement Solutions
Suitable for	Strategic products	Leverage products	Bottleneck (critical) products	Non-critical (standard, routine) products
Objective	Building mutual commitment for long-term partnership	Obtaining the best short-term offers	Ensuring short- and long-term supply and reducing procurement risk	Reducing logistical complexity. Improving operational efficiency. Reducing the number of suppliers.

Source: (van Weele, 2018)

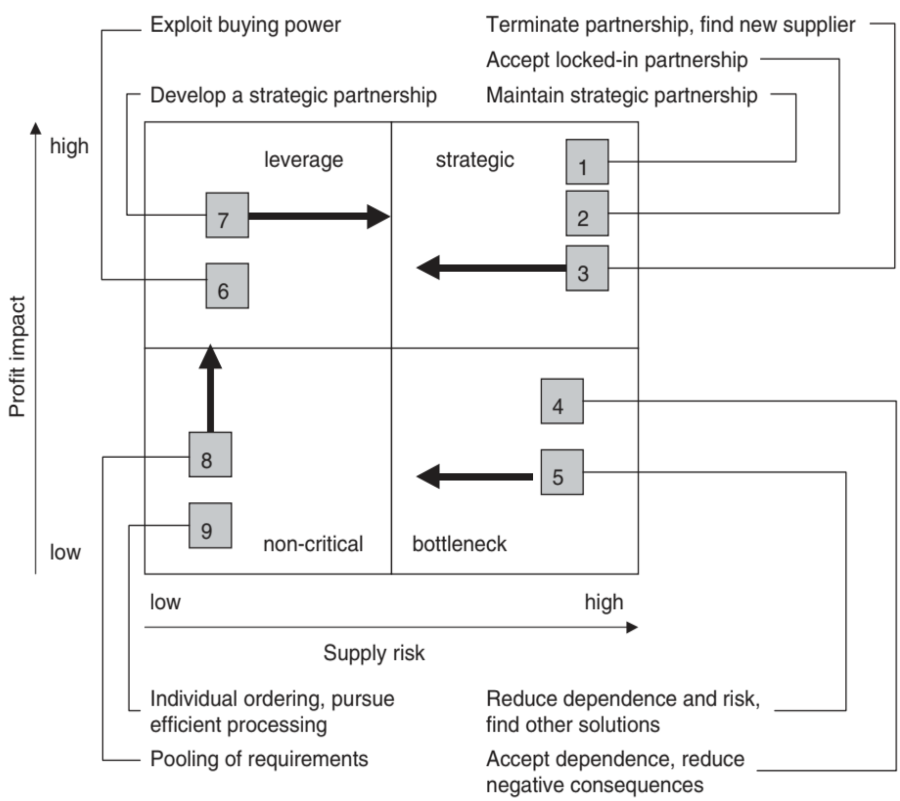

Figure 3.4: Overview of Different Procurement Strategies for All Portfolio Quadrants (Within Quadrants and Oriented Toward Movement)

Source: (Caniëls & Gelderman, 2005)

Quadrant – Strategic Products

1. **Maintain Strategic Partnership** For products with high procurement risk and high financial impact, this strategy focuses on sustaining a strategic partnership, as there is a strong, cooperative relationship with mutual understanding between both parties.
2. **Accept a "Locked-in" Partnership** In cases where the company is effectively "locked into" a relationship with a particular supplier, this strategy accepts the situation. The goal is to make the best out of an involuntary relationship with the supplier.
3. **Terminate the Partnership and Seek a New Supplier** The supplier is expected to behave as a strategic partner, but there is too much uncertainty. The company feels it cannot control the supplier's behavior and decides to look for another supplier and build a new relationship. This is clearly a difficult and demanding task.

Quadrant – Bottleneck (Critical) Products

4. **Accept Dependency and Minimize Negative Effects.** The primary focus is ensuring supply, even at additional cost. Examples include maintaining extra inventory or arranging consignment[1] stock with suppliers. Risk analysis helps identify the most critical bottlenecks and consider the implications. Contingency planning can be a potential response to unexpected dependencies.
5. **Reduce Dependency and Seek Alternatives.** This strategy aims to lessen dependence on a specific supplier. Common approaches include broadening product specifications or finding new suppliers. According to the authors, supplier dominance is most evident when the buyer fully accepts a dependent position.

Quadrant – Leverage Products

6. **Exploit Bargaining Power and Increase Strategic Advantage Over Suppliers.** The company uses competitive bidding. Since suppliers and products are interchangeable, there is no need for long-term contracts. A

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[1] Consignment – the owner of the goods (the supplier) charges only for the material used. (Often, the supplier is based abroad.) This is a type of intermediary sale (similar to commission-based sales, where both parties are from the same country).

coordinated procurement approach is used, typically involving a centrally negotiated master agreement with preferred suppliers.

7. **Develop Strategic Partnerships.** Here, the company abandons financial leverage and opts for a strategic partnership—only if the supplier is both willing and able to contribute to competitive advantage. This approach is viable primarily with technologically advanced suppliers. The relationship begins to resemble that of the strategic product quadrant, aiming for balanced power and long-term collaboration.

Quadrant – Non-Critical Products

8. **Consolidate Procurement Requirements.** This strategy aims to reduce procurement complexity. It recommends standardizing products and establishing contract-based supplier relationships, enabling automation and simplification of routine tasks, stock optimization, and bulk ordering over time.
9. **Individual Ordering and Efficient Order Processing.** When consolidation is not feasible, products into larger purchase volumes, individual ordering with a procurement card may be used—still targeting reduced administrative costs of routine procurement.

Despite its advantages as a foundational portfolio model, the Kraljic Matrix also exhibits notable shortcomings:

– **Unclear Classification and Dimension Definitions.** In practice, companies may misclassify 80% of their procurement items as strategic simply because they are critical to operations. This could result in excessive effort on strategic analysis and partnerships, reducing bargaining power by overlooking alternative procurement strategies.
– **Ignoring the Supplier's Perspective.** Perhaps more critically: The Kraljic matrix does not consider the supplier's view of the buyer. For example, a company spending €20,000 at a local café may have more more influence than it would with a significantly larger spend on advertising services from a global corporation like Google. (The Kraljic Matrix - How to Optimize Purchasing Costs and Risks, 2022)

4 Conclusion

Research and practical experience demonstrate that, in an era of increasing global interconnectivity and supply network complexity, it is essential to develop adaptive and flexible practices. The Kraljic Matrix, widely recognized as a standard model for developing procurement strategies through supplier portfolio analysis, proves to be an effective tool for classifying suppliers and formulating strategies aimed at reducing risk and enhancing organizational resilience in supply chains.

By using the matrix, procurement products can be classified into distinct categories, allowing for the development of tailored strategies for each group. Key procurement strategies include establishing partnerships, utilizing competitive utilizing, ensuring continuity of supply, and effectively managing procurement categories. These approaches contribute to better disruption management, cost optimization, and improved efficiency–all of which are critical for maintaining stability in today's dynamic and uncertain business environment.

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CITY LOGISTICS – A COMPLEX, YET MANAGEABLE SYSTEM

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City (urban) logistics involves the management and optimization of distribution processes in urban areas, primarily focusing on the flow of goods, but occasionally also on people and information flows. In urban settings, freight traffic accounts for 10-15% of all distances travelled, causing issues such as congestion, environmental pollution, and road damage. Particularly, the activities of last-mile logistics in cities constitute a significant portion of transportation costs. Managing urban logistics involves various stakeholders, from city authorities, carriers, and merchants to residents and urban planners, all of whom play a crucial role in shaping and implementing effective urban logistic solutions. Solutions in this field can be categorized into soft measures, which focus on improving existing systems without major investments, and hard measures, which involve physical infrastructure changes and require more substantial investments. Some of the most vital measures include concepts like time windows, delivery points, parcel lockers, electric vehicles, consolidation centres, and even modern solutions such as crowdshipping. For smaller cities, which are common in Slovenia, these measures need to be adapted. National guidelines for the preparation of the Urban Logistics Management Plan were recently developed, laying the foundation for holistic and sustainable urban logistics in Slovenia.

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1 What is Urban Logistics?

Urban (also known as city) logistics is a complex concept referring to the management and optimization of distribution processes in urban environments. It primarily concerns the flow of goods within city areas, though it occasionally also includes the movement of people and information, especially in the context of smart cities. This chapter explores the need for managing urban logistics, understanding why its effective management is crucial for improving city performance and enhancing the quality of life for urban residents.

Batarlienė and Bazaras (2023) estimate that, in urban environments, freight transport accounts for 10–15% of the total travel distances. As freight flows in cities increase, various issues arise, such as loading and delivery delays, elevated environmental pollution and noise, a shortage of heavy vehicle drivers, road degradation, and more. From a supply chain perspective, last-mile delivery[1] operations account for 28% of total transport costs in supply chains (Papoutsis & Nathanail, 2016). Additional challenges arise when deliveries must occur within narrow time windows due to recipient needs, or when the recipient must be present at home or another designated location (Oršič et al., 2022). According to UN projections, nearly 70% of the world's population will live in urban areas by 2050 (United Nations, 2019), making the issue of urban supply and traffic management increasingly urgent and relevant.

In both practice and literature, various terms are used to describe urban logistics concepts. Cardenas and colleagues (2017), following an extensive review, defined three levels of freight analysis in urban environments (see Figure 1.1). The macro level represents urban logistics in its truest sense and focuses on stakeholder interactions and relationships. Its primary distinction lies in its focus on improving citizens' quality of life. Objectives at this level of urban freight regulation include long-term measures and goals such as land use, emission reduction, and improved urban living conditions. Decision-makers at the macro level, address logistics from a systemic perspective, requiring a holistic approach to challenges—this is strategic-level management. The meso or intermediate level focuses on the distribution of

[1] ***Last-mile delivery:*** Since the term originates from English-speaking contexts where imperial units are used, the expression "last mile" is also most commonly used in Slovenian, even though "last kilometer" might be more accurate. One mile is approximately 1.6 kilometers. The term refers to the very final segment of the journey that goods travel through the supply chain—namely, the delivery to the end user or consumer of a shipment.

goods within urban areas, from the point they enter the city zone. Key challenges are related to transport systems, logistics infrastructure, location decisions, consolidation schemes, storage, the interaction between freight and passenger vehicles and infrastructure, externalities, and the overall efficiency of freight transport management. This level deals with the interplay between transport and logistics systems. The micro level refers to last-mile delivery and pickup operations and focuses on the distribution of goods at the micro level. It covers the final or initial stage of transport within the supply chain. Main goals include, for instance, multi-stop routing problems and restricted access to certain urban areas that lack adequate logistics infrastructure (see Figure 4.1).

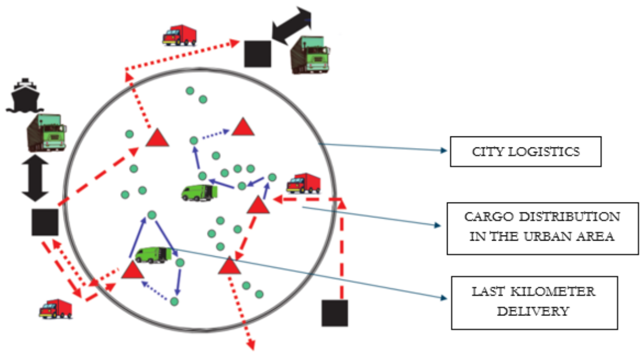

Figure 4.1: Three Levels of Urban Freight Movement
Source: adapted from Cardenas et al. (2017)

1.1 Challenges of Urban Logistics

The growth of freight traffic in urban areas increases congestion, as both goods and passengers add to traffic density. Urban freight distribution faces challenges, includingcongestion, reduced travel speeds, and the need for frequent deliveries due to limited storage capacity in urban environments and the rise of e-commerce. Additionally, there is an increasing demand for reverse logistics in cities—such as recycling—and growing concern over social impacts, including accidents and pollution. Urban areas are subject to strict regulatory pressures due to high population densities and diverse regulations. Together, these factors present challenges that efficient urban logistics must address and resolve (Rodrigue, 2020).

The problems associated with freight traffic in urban environments, and targeted by urban logistics solutions, include:

- Congestion and traffic jams: Freight vehicles contribute to road congestion, leading to longer travel times and increased fuel consumption.
- Air pollution: Freight vehicles, especially those powered by fossil fuels, emit pollutants that degrade air quality and harm public health.
- Noise: Freight traffic generates noise, which can disturb residents and reduce the quality of life in city centers.
- Safety risks: Increased freight traffic density raises the likelihood of traffic accidents, particularly in interactions with pedestrians and cyclists.
- Limited parking and spatial contraints: Freight vehicles often occupy large parking areas, potentially creating shortages for personal vehicles and other users. Providing delivery zones and parking also means limited space for green areas and infrastructure for non-motorized transport.
- Infrastructure wear: Heavy freight vehicles accelerate the deterioration of road infrastructure, and may cause vibrations that negatively affect nearby buildings, leading to increased maintenance costs.
- Energy efficiency: Inefficient urban logistics practices can lead to higher fuel consumption and increased greenhouse gas emissions.

Batarlienė and Bazaras (2023) identified the most important factors influencing urban logistics, ranked in order of importance:

1 Urban road infrastructure
2 Traffic regulations
3 Geographic location of the city
4 Cooperation between city administration and businesses
5 Geographic distribution of businesses
6 Cooperation among businesses
7 Legal frameworks
8 Innovation and information technology

1.2 Stakeholders in Urban Logistics

Key stakeholders in urban logistics include shippers (manufacturers, wholesalers, retailers), receivers (end consumers), public administration (national, regional, and municipal), logistics service providers, city residents, and others (e.g., planners, traffic engineers and carriers, educational institutions, non-governmental organizations) (de Carvalho et al., 2019). These stakeholders are various individuals, organizations, and entities that have an interest in, or influence over the planning, implementation, and management of urban logistics systems.

The roles of the most important stakeholders are outlined below:

- City authorities: Urban managers (e.g., municipal administrations) and urban planning departments are central stakeholders responsible for regulating and shaping urban logistics policies and infrastructure.
- Transport companies: Freight carriers, logistics service providers, and delivery companies are key stakeholders involved in the actual movement of goods throughout urban environments.
- Retailers and businesses: Retailers, wholesalers, and businesses operating in or relying on urban areas are significant stakeholders, as they both generate and receive goods in cities. They are often involved in last-mile delivery planning.
- Residents: City residents are crucial stakeholders affected by urban logistics activities, including noise, pollution, and traffic congestion. Their feedback and behavior can influence logistics strategies.
- Urban planners: Urban planners and architects contribute to the design of urban spaces, including transport infrastructure, distribution centers, and logistics hubs.
- Trade associations: Trade associations representing various sectors, such as retail, manufacturing, and transport often participate in discussions and negotiations related to urban logistics policies and regulations.
- Technology providers: Companies offering technological solutions, such as route optimization software, IoT sensors, and telematics, are stakeholders that enable the implementation of smart urban logistics.
- Non-governmental organizations (NGOs): NGOs with interests in urban planning, sustainability, and transportation can advocate for environmentally friendly logistics practices and can influence urban logistics policies.

2 Strategies and Measures for Managing Goods Flows in Cities

Urban logistics solutions are generally divided into two categories: *soft* and *hard* measures.

Soft measures do not require major investments or infrastructure changes. Instead, they focus on improving existing systems and practices. These include awareness-raising, information sharing, and encouraging cooperation among various stakeholders such as retailers, carriers, and local authorities. Hard measures, on the other hand, involve physical infrastructure changes. These include the construction of new roads, terminals, or warehouses, the introduction of access restrictions, time windows for freight traffic, and other actions requiring significant investment and long-term planning. The acceptability of such measures depends on specific characteristics of each urban environment, especially the factors described earlier.

Based on the requirements for managing flows in cities and a comprehensive literature review, Papoutsis and Nathanail (2016) identified six categories of urban logistics strategies, each with different objectives and elements:

- New distribution and logistics models for operators: Mostly private-sector measures such as off-peak deliveries, consolidation schemes...
- Capacity sharing: Measures in which multiple operators share existing infrastructure or vehicles, e.g., multi-purpose traffic lanes.
- Infrastructure development and vehicle features: Includes ICT-based measures, ITS and vehicle technology, and construction of distribution centers or micro pick-up locations.
- Access control: Measures that restrict access to urban areas based on environmental criteria, vehicle weight, or traffic calming measures.
- Activity-enabling regulation: Regulatory measures imposing limitations on logistics processes such as time windows, parking rules, and related soft measures.
- Enforcement, route optimization, and training: Includes law enforcement, driver training (e.g., eco-driving), and route optimization tools.

These broad strategy categories serve as a framework within which cities plan and implement tailored actions suited to their environments. Based on assessments by urban logistics experts, some of the most impactful measures or initiatives that significantly contribute to regulating distribution flows within city centers can be ranked by importance— from most to least effective (Batarlienė & Bazaras, 2023):

1 Prohibition of heavy vehicles entering the city center,
2 Environmental taxes for urban freight transport,
3 Creation of a network of small self-service terminals on the city outskirts,
4 National incentives for the purchase of environmentally friendly vehicles,
5 Integration of logistics companies into a unified urban freight transport information system,
6 Relocation of large businesses to the urban periphery,
7 Tax relief for businesses cooperating in urban freight transport,
8 Government support for IT adoption and integration into the smart city system.

In the following sections, we describe the most commonly highlighted measures or initiatives in urban logistics and the management of freight flows in urban environments.

Managing and Optimizing Urban Freight Traffic Flows

Managing freight traffic flows involves strategies and practices aimed at directing, controlling, and optimizing the movement of goods from their point of origin to their final destination. In urban contexts, this refers specifically to the movement of goods from their point of entry into the city to their destination, or vice versa. This involves planning optimal routes, selecting the most efficient means of transport, reducing congestion, and improving overall transport efficiency. Optimization focuses on the use of mathematical models, algorithms, and technologies to enhance efficiency and reduce costs associated with freight transport. The goal is to find the best solutions to specific logistical challenges, such as minimizing travel distance, reducing delivery times, and vehicle capacity utilization.

Such initiatives are driven by individual delivery providers and carriers. Examples include: vehicle tracking systems, route optimization software, and similar tools. On the public side, city authorities may implement measures that require changes to delivery patterns. These changes may affect routes, delivery locations, vehicle types, and more.

Most of the measures described in the following sections are at least indirectly aimed at optimizing freight flows within cities.

Time Windows and Other Access Restrictions

Time windows for urban freight deliveries are specific time intervals during which delivery or pick-up of goods is permitted in certain city zones. This is one of the approaches cities employ to reduce traffic congestion, noise, and other negative externalities associated with freight transport in city centers—particularly by minimizing traffic during peak traffic hours.

By restricting deliveries to specific time slots, the number of freight vehicles operating during peak times can be reduced. This, in turn, improves overall traffic flow, lowers emissions, and minimizes noise. Time windows allow carriers to plan and optimize delivery routes more effectively, which can lead to greater efficiency and cost savings when implemented appropriately. While time windows bring numerous advantages – especially in terms of improving urban quality of life for residents and visitors–they may also pose challenges for carriers, who must adapt their operations to meet the restrictions. This may lead to increased costs, such as the need for night-time deliveries or hiring additional staff. Some cities allow flexible time windows that adjust based on traffic conditions, city events, or other factors. Modern technologies such as telematics and advanced fleet management systems enable carriers to better monitor and plan deliveries in accordance with time windows. Sánchez-Díaz et al. (2016) identified a wide spectrum of approaches to encouraging deliveries outside of peak traffic hours. These range from market-driven methods–such as voluntary schemes without specific regulations, congestion-based infrastructure pricing, and incentive-based programs–to more regulatory approaches, such as granting access to freight vehicles outside peak hours, but enforcing (or applying existing) noise level regulations, restrictions on the use of loading/unloading zones at certain hours, or prohibitions that require carriers to deliver at night. On the receiving end, recipients are also affected by the shift to off-peak deliveries, which often means night-time delivery. Sánchez-Díaz et al. (2016) identified three main schemes for receiving night or off-peak deliveries: staffed reception, unattended reception, and facility manager-coordinated reception in large traffic generators. The costs, risks, and reliability of each scheme differ significantly depending on the model chosen.

In addition to time windows, cities implement various access restrictions based on vehicle weight, EURO engine emissions classifications, and similar criteria. For European cities, access restrictions by location are compiled on the website https://urbanaccessregulations.eu/.

Delivery Zones and Related Spatial Restrictions

Delivery zones and other spatial restrictions are integral components of modern urban logistics strategies implemented by city authorities to optimize freight transport in urban centers. Delivery zones are specifically designated areas used exclusively for the loading and unloading of goods. Their locations and dimensions are determined based on analyses of traffic flows, accessibility, and the needs of local businesses. This is one of the easiest measures to implement and primarily addresses the issue of delivery vehicles occupying non-designated spaces. Additional spatial restrictions, such as specific delivery-only zones or prohibitions on freight traffic in certain areas or streets, are introduced to reduce the broader negative impacts of freight transport on the urban environment.

The implementation of such measures brings several advantages for different stakeholders. For shippers and receivers, designated delivery zones contribute to more predictable and efficient delivery processes. These zones are designed to minimize conflicts with other road users, thereby improving safety and reducing space occupation for other transport users.

Hammami (2020) identifies several factors that should be considered when planning delivery zones in urban environments:

- type of businesses and activities in the area;
- size of retail spaces;
- how deliveries are currently made: using existing delivery bays, sidewalks, or other traffic areas—or none;
- type of vehicles used (large truck, small truck, car);
- duration of loading/unloading operations;

- number and schedule of daily/weekly deliveries;
- suitability of placing delivery zones on existing infrastructure.

Parcel Lockers and Other Self-Service Pickup Options

Parcel lockers are automated pickup stations where customers can collect their packages independently. These lockers are typically located at strategic points such as shopping centers, transit hubs, and gas stations, allowing customers to retrieve parcels at their own convenience regardless of courier operating hours. This approach reduces the need for repeated delivery attempts, which, in turn, decreases congestion, and emissions. One notable limitation of parcel lockers is parcel size. Therefore, other self-service points or lockers are often used to accommodate larger or specific types of goods, such as refrigerated items. Some retailers use these points as an alternative to home delivery, allowing customers to collect their orders while commuting or running errands. By introducing parcel lockers, the responsibility for last-mile delivery is effectively shifted from delivery providers to end consumers themselves. This in turn also changes traffic flow patterns. Eliyan et al. (2021) showed that, considering the travel distance by recipients and sufficient locker occupancy, the carbon footprint of parcel delivery can be reduced by up to 50%.

Electric Vehicles and Cargo Bikes

Electric vehicles (EVs) are increasingly being adopted in urban logistics as an alternative to conventional fossil-fuel-powered vehicles. With zero tailpipe emissions and quiet operation, EVs are well-suited for urban areas where air quality and noise pollution are significant concerns. Consequently, city authorities often promote—or even mandate—the use of EVs by offering benefits such as reduced tolls, access to city centers, and dedicated parking zones. However, EVs in urban logistics also face several challenges, including limited driving range, longer charging times, and insufficient availability of fast-charging infrastructure.

A related alternative for performing small-scale delivery tasks or for use in bike-sharing schemes are cargo bikes, especially those with electric assist. These allow for fast and efficient short-distance deliveries while avoiding traffic congestion and vehicular restrictions commonly found in city centers. However, cargo bikes are limited by reduced load capacity, vulnerability to adverse weather conditions, and the physical effort required to operate them, even with electric assistance.

Urban Consolidation Centers

Urban Consolidation Centers (UCCs) are transshipment terminals, usually located on the outskirts of major cities. Their purpose is to optimize infrastructure, operations, and services between interurban and intra-urban segments of the supply chain. At UCCs, goods arriving from outside urban areas are collected and consolidated for last-mile delivery. The main goal of UCCs is to eliminate the need to deliver partial loads to city centers or similar destinations (e.g., construction sites, airports) by providing facilities where shipments are combined for further delivery to urban areas using appropriate vehicles with high load utilization (Gogas & Nathanail, 2017).

Despite their potential environmental and societal benefits, the main obstacle to implementing UCCs is the lack of a sustainable business model. As a result, UCCs are often heavily subsidized and cease operations when subsidies expire (Kin et al., 2016). The challenge is even greater in smaller cities, where achieving the critical mass of users is needed to make such centers financially viable.

A best-practice example of a successful UCC in a smaller city is Lucca, with approximately 80,000 residents and an area of just over 185 km². The city center, enclosed by 4.2 km of Renaissance walls, forms the core of a vibrant commercial system with more than 1,400 businesses, leading to significant traffic challenges. Specific traffic measures such as time windows and pedestrian zones are in place in the historic center. In 2005, the LuccaPort Urban Consolidation Center was established. It offers typical services, including transshipment, optimized delivery organization, dedicated warehouses, a fleet of electric vehicles, and advanced ICT services for tracking and information sharing across the logistics chain. LuccaPort performs over 120 daily deliveries, operates at full capacity, and makes about 15 deliveries per trip–representing 15% of urban deliveries and reducing the number of freight vehicles in the historic center by 44% (Foltyński, 2014).

Micro Urban Logistics

Micro urban logistics integrates concepts such as hyperlocal fulfillment and micro consolidation centers. As such, it is becoming a key strategy for optimizing deliveries in city centers (Moline, 2018). The concept involves setting up small, localized distribution hubs within cities that enable faster and more efficient short-distance deliveries, thus reducing dependence on large, centralized warehouses. It allows businesses to respond more quickly, shortens transport times, and reduces delivery costs. Micro logistics also helps reduce traffic and emissions, contributing to a more sustainable urban environment.

A key concept within micro urban logistics is the simplified form of consolidation centers, so-called "microhubs"–small distribution centers or warehouses strategically located in or near city centers. These are designed to collect, sort, and distribute goods in smaller urban areas or districts. Their implementation often includes options for self-service pickup by end customers (Rosenberg et al., 2021). Using microhubs reduces the need for heavy trucks to enter urban centers, as goods can be brought to the hub using larger vehicles and then delivered with smaller, often eco-friendly vehicles such as electric vans, bicycles, or even on foot.

In contrast to larger UCCs typically situated on urban peripheries, microhubs focus more on last-mile delivery and are closer to final destinations. While UCCs serve as collection and sorting points for incoming goods, microhubs function as satellite units that enable faster, more flexible deliveries in city centers–often using bikes, small carts, or walking couriers.

Crowdshipping

Crowdshipping is a concept that involves engaging the public to pick up and deliver parcels, ideally on their pre-planned routes. This means that individuals—such as public transit riders—can act as couriers during their daily routines. In this context, the availability of a large number of ordinary citizens connected by mobile devices has created numerous opportunities for last-mile delivery in a more environmentally friendly manner. However, due to numerous logistical challenges, assigning delivery tasks to the crowd is a complex, multi-layered process (Ghaderi et al., 2022).

A successful pilot project of crowdshipping was conducted in the city of Jyväskylä, Finland. This test involved a crowd-based delivery service using the "PiggyBaggy" platform for book deliveries from the city library between March 15 and April 30, 2014. Despite the low compensation (2–5 euros per delivery), the initiative quickly attracted many drivers, mostly cyclists. Paloheimo et al. (2016) calculated that this system could reduce transport-related resource usage by up to 55% with added benefits such as increased social cohesion and economic savings.

Reverse Logistics

When planning and managing goods flows, the focus is often solely on incoming flows to the city–such as raw materials, deliveries, and support materials–while the importance of reverse flows is often neglected. These include products generated within the city center, waste, and similar outputs. Therefore, it makes sense to integrate urban logistics with the concept of reverse logistics. Reverse logistics refers to the processes and activities related to collecting, transporting, and processing used, unwanted, or surplus products and materials from urban areas back to production or processing centers. This approach is essential for sustainable urban management, as it enables waste reduction, resource optimization, and lower environmental impact (Rubio et al., 2019).

3 Urban Logistics in the Slovenian Context

Urban logistics in Slovenia faces specific challenges, particularly in the context of small towns. Slovenian towns often feature distinctive historical centers characterized by narrow streets, small squares, and unique architecture heritage. These features complicate traffic and difficult access for larger freight vehicles and pose a greater risk of damage to older buildings due to heavy traffic. In smaller towns, the short distances between delivery points require greater flexibility in planning and managing freight flows. Furthermore, due to limited coverage areas and fewer potential customers, the implementation of large-scale or costly logistics measures is challenging because the critical mass needed to justify and sustain these services is often lacking. While larger Slovenian cities have introduced numerous urban logistics improvements–such as urban distribution centers, restricted access zones, and electric delivery vehicles–such solutions must be adapted to suit smaller towns. The use of small electric vehicles or even cargo bikes is more appropriate in small urban environments than larger trucks, which struggle with the spatial limitations of narrow streets. Distribution centers in such towns can be smaller and more flexible, adapted to shorter distances and specific resident needs, or combined with parcel lockers and shared pickup points. Collaborating with local stakeholders is also crucial to developing solutions tailored to the specifics and needs of each town.

In the Slovenian context, National Guidelines for the Preparation of Urban Logistics Management Plans (Lep et al., 2022) were recently developed. According to the Act on Comprehensive Transport Planning (Official Gazette of the RS, 130/22), urban municipalities with more than 100,000 residents are required to prepare an Urban Logistics Management Plan (ULMP), while other municipalities are encouraged to incorporate urban logistics measures into their Municipal Sustainable Urban Mobility Plans (SUMPs). This plan serves as a prerequisite for national co-financing of freight consolidation measures in cities.

The ULMP preparation process consists of seven stages, ranging from preparation and outlining the desired state to analyzing the current situation, defining measures, strategic planning, and long-term implementation. It is vital that the ULMP incorporates a sustainable, long-term vision based on a comprehensive assessment of current and future conditions and involves all relevant stakeholders. The ULMP offers an optimal framework for economic efficiency of urban logistics while promoting a environmental sustainability. Therefore, it is essential to consider combining conventional and unconventional delivery methods, such as electric vehicles, cargo bikes, and the integration of freight and passenger transport. The guidelines for ULMP development recommend that urban freight flows and urban logistics in the Slovenian context focus on the implementation of ICT solutions, restricting freight vehicle access to city centers, stakeholder inclusion, accommodating the demands of e-commerce, and adopting environmentally friendly vehicles.

4 Conclusion

Urban logistics is facing growing challenges as a result of urbanization, increased consumption, and changing consumer habits. Managing freight traffic and deliveries to and from cities is essential for maintaining urban vitality and supporting economic development. Modern approaches to urban logistics management are increasingly supported by digitalization, which plays a key role in optimizing urban logistics.

These technologies enable better delivery route planning, real-time freight tracking, and efficient communication among all stakeholders. Since proper and effective urban logistics management contributes to sustainable development, emission reduction, and improved quality of life in cities, this is a topic of critical importance in today's world.

In small towns–such as many across Slovenia–urban logistics challenges manifest differently. Limited infrastructure, narrow streets, and historic city centers impose additional constraints on delivery planning and execution. Solutions developed for larger cities must be adapted to fit the specific characteristics and needs of smaller towns. In the Slovenian context, it is crucial to combine traditional and modern approaches to ensure an efficient, sustainable, and adaptable urban logistics environment.

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How to Distribute Products? On an Optimal and Sustainable Distribution Strategy

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Distribution within the framework of logistics processes encompasses a series of operations and procedures that enable the delivery of goods from the creation and manufacturing phase all the way to the end usage by the consumer. These processes include activities such as transportation, warehousing, inventory management, location analysis, and information processing. The central purpose of distribution logistics is to ensure that products arrive at the consumers flawlessly and efficiently. Here, transportation plays the role of transferring goods, meaning that the decision on the mode of transportation is an important segment of setting an appropriate distribution strategy. In addition, choices are influenced by factors such as the characteristics and type of goods, competitive factors, demands for the complexity of the distribution channels themselves, and the like. The main decisions thus include the length of the distribution channels, the use of direct or indirect forms of distribution, types and varieties of channels for offering and distributing goods to end consumers, and the extent of outsourcing. The key objectives of establishing distribution channels include ensuring the correct presence of products on the market, increasing sales opportunities with positioning strategies and promotions, and effective participation in determining influences on the operational distribution activities.

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1 What is distribution? Which parts of business does it cover?

Logistics–and distribution as a part of it–are two processes in supply chains. Several groups of actors can be identified based on the different stages of goods movement along the chain:

- Suppliers supply the chain with raw materials, components, semi-finished products, finished products, and other components and materials.
- Manufacturers are engaged in product development and production. In some cases, raw materials such as wood and coal move directly into the chain.
- Intermediaries:
  - Wholesale distributors are intermediaries between manufacturers and other intermediaries, providing products from the source.
  - Brokers facilitate buying and selling between suppliers and buyers, without taking ownership of inventory.
  - Retailers sell goods to end consumers or businesses.
- End consumers can be either business or individual consumers.

The way supply chain elements are combined leads to different distribution channels. The nature of demand, production processes, and the influence of the main channel determine both the scope and the number of channel members. According to Kajba et al. (2023), and in line with the concept of constant factors in supply chain systems–namely products, services, processes, and systems–each element within the supply chain is both influenced by and interdependent with others, leading to complex and interconnected relationships. This integration enables the optimization of material, information, and financial flows, but it also increases the complexity of management. As individual processes and systems continuously adapt to changes in supply demand, businesses must remain flexible and continuously monitor efficiency in order to maintain a competitive advantage and ensure smooth distribution flow.

In logistics, distribution refers to processes and activities that direct the flow of goods from their development and production to the end consumer. These activities include transportation, warehousing, inventory management, location analysis, and information processing. The main goal of distribution logistics is to ensure the efficient and smooth delivery of finished products to consumers.

It is important to distinguish between a "distributor" and "distribution". A distributor is an intermediary in the distribution channel who does not manufacture its own products but purchases and resells or mediates them. Thus, distributors typically purchase goods in larger quantities and then distribute them to more consumers or buyers in smaller units. A distributor is therefore a key element in ensuring that products reach end consumers.

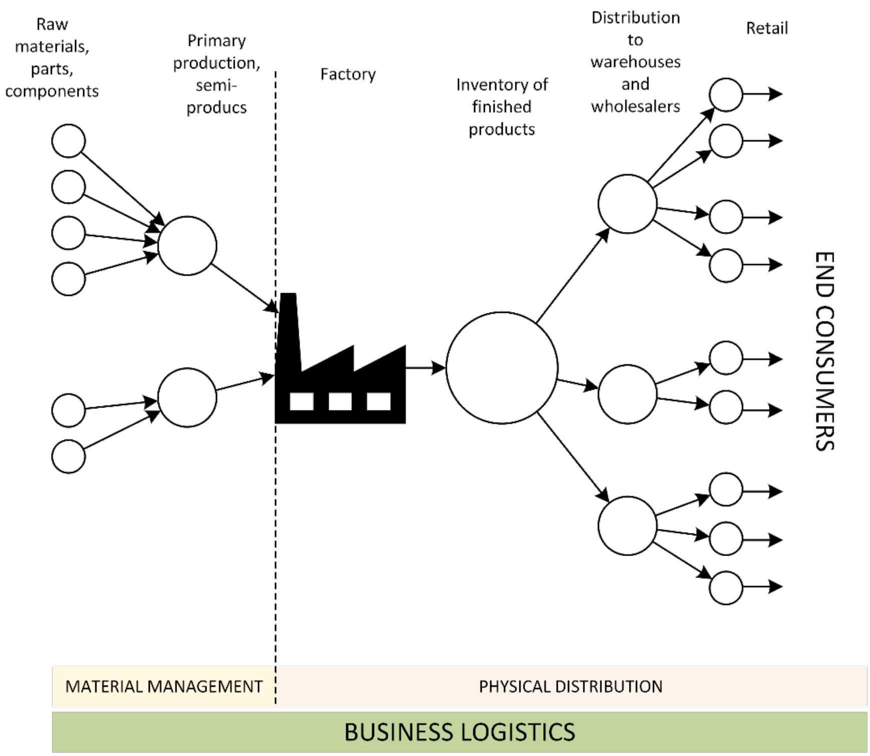

Figure 5.1: Distribution and Transport in Supply Chains
Source: adapted from (Murphy & Knemeyer, 2018)

On the other hand, "distribution" describes the entire process and not just one element in the channel. Distribution encompasses activities related to the movement of goods, including transportation, warehousing, order management, location analysis, and similar activities. According to Ross (2015), distribution within the distribution system includes activities such as transportation, warehousing, inventory management, materials handling, order management, location analysis, industrial packaging, and data processing and communication networks. Overall, distribution is a key component of the logistics chain that ensures products and services reach consumers correctly and efficiently, whether they travel directly from the manufacturer or via a distributor.

The processes of distribution and transport in supply chains are illustrated in Figure 5.1. Here, circles symbolize facilities where inventories are stored, while lines with arrows represent movement or distribution processes managed by distributors. The supply chain continues both to the left and right of the displayed segment.

2 Modes of Transport and Distribution, their Environmental Impact and Costs

In distribution and logistics networks, transport functions as the "carrier" of goods through the supply chain. The transport network often coincides with the distribution network, focusing on the physical movement of goods. While we refer here to the movement of physical goods, transport may also represent the movement of, for instance, information, monetary flows, and so on. Planning these networks is closely tied to overall supply chain planning and its flow; consequently, transport management in distribution is also crucial for an efficient supply chain. Various modes of transport–rail, road, water, air, or pipelines–offer users numerous choices. Despite the wide array of options, selecting the right mode and service provider can be challenging. Key factors in selection are (Ballou, 2004):

- Cost, determined by basic transport expenses, possible additional costs, and relevant expenditures, such as fuel, labor, and depreciation.
- Average transit time, or the average duration of shipment travel from the origin to the destination.
- Transit time variability, meaning variations in delivery time caused by external factors such as weather or congestion.
- Loss and damage, referring to the carrier's ability to transport goods without damage or losses.

Therefore, the selection of a service is not focused solely on cost but also on the quality and reliability of the service. Some transport modes can be combined for greater efficiency in terms of intermodal or multimodal transport; for example, goods may be transported by rail and then delivered locally by truck. Nevertheless, the "door-to-door" approach is key for effective and timely delivery, and consequently for the efficient operation of distribution processes.

Road transport by trucks is often a key element in the distribution chain, especially for semi-finished and final products. Unlike rail, which transports larger quantities of raw materials and cargo, trucks offer a solution for smaller shipments, providing greater flexibility in distribution. One of the main advantages of road transport is the possibility of "door-to-door" delivery. This means there is less cargo handling between the origin and the final destination, reducing the need for additional loading or unloading, as is common in rail or air transport. Trucks also have an advantage in terms of availability and frequency of transport, as schedules can be quickly adjusted according to customer needs. The road transport market includes various types of carriers, including contract carriers who specialize in specific clients and offer customized services (without the client needing to own the vehicles). Of course, trucks cannot transport as many different types of cargo as railways, primarily due to road limitations such as dimensions and weight. Nevertheless, trucks provide fast and reliable delivery of bulk goods or goods on smaller intermodal units, such as pallets. The ability to quickly load a vehicle and immediately begin transport is a major advantage, especially for smaller quantity shipments, where trucks dominate the market compared to rail, which requires larger volumes for optimal efficiency. Road transport by trucks is therefore indispensable in the modern distribution chain due to its flexibility, speed, and efficiency.

Rail Transport is a key element of the physical distribution system, enabling long-distance freight transport. It is especially suitable for transporting raw materials such as coal, timber, and chemicals, as well as lower-value products like food, paper, and wood products. A distinctive feature of rail transport is that the majority of time (in some cases up to 80%) is spent on processes such as loading, unloading, terminal switching, and shunting, which results in relatively low operational speed and a shorter daily mileage per wagon. The railway transport system operates under two legal forms—public and private carriers. Public carriers provide services to the general public, while private carriers focus primarily on the needs of a specific owner.

Most rail traffic is conducted by public carriers. It is important to note that the basic unit of rail freight is the "lot", representing a specific quantity of goods, typically corresponding to the capacity of one railcar. To increase efficiency, multiples of lots are often used, especially for larger shipments. Modern railways offer various services tailored to market needs–from specialized wagons for specific cargo types to flexible services allowing route and destination changes during transport. In a distribution context, rail transport offers numerous advantages, such as greater transport capacity, flexibility, and cost-effectiveness, especially for large-volume, long-distance freight.

Despite its higher cost, *air transport* has become an essential part of the global distribution network, primarily due to its unmatched speed in crossing long distances. Commercial aircraft capable of high speeds allow rapid delivery, although additional time factors such as takeoff, landing, and airport delays must be considered. While air transport is sensitive to weather and other obstacles, its reliability is high. With continuous technological advancements and the emergence of larger aircraft, limitations in volume and payload are decreasing, potentially making air freight more affordable in the future. One added benefit of air transport is the reduced risk of loss or damage compared to ground transport. Packaging requirements for air transport are less stringent, and theft at airports is relatively rare. Modern air freight covers a wide range of services, from regular domestic to international carriers that connect global markets and facilitate international trade. All of this underscores the growing importance of air transport in modern distribution networks.

Water transport remains one of the classic modes of transport, still widely used due to its exceptional carrying capacity, despite certain limitations. Its operation is confined to specific geographic conditions, as inland waterway transport is viable mainly along continental routes, requiring specific locations for cargo originators. Compared to rail transport, water transport is slower, with average speeds up to 15 km/h. However, its capacity is impressive; barges–flat-bottomed vessels designed for river and coastal transport without their own propulsion–can carry up to 4,000 tons. Technological improvements such as satellite navigation enhance the efficiency and reliability of this mode. Water transport is also economically adaptable, as most goods travel under minimal economic regulation. Loss and damage are minimal, particularly for bulk low-value cargo. However, transporting more valuable goods requires additional care and appropriate packaging. The energy efficiency of water transport is its key advantage, enabling the movement of large volumes over long distances with less fuel consumption than other modes. Comparisons show that barges consume less energy per ton-kilometer than other transport methods, highlighting their important role in the distribution chain.

Pipeline transport is a specialized method currently most efficient for transporting oil and refined petroleum products, although there are efforts to expand its use to other cargo types. A key feature of pipeline transport is its slowness, with speeds between 4.8 and 6.5 km/h. However, its continuous operation–24 hours a day, 7 days a week–ensures high efficiency and reliability. Pipelines offer high transmission capacity under full operation. In terms of reliability, pipelines are among the top, as their functioning is rarely disrupted by external factors like weather, and pumping equipment is extremely dependable. From a distribution standpoint, loss and damage are minimal, since liquids and gases are less susceptible to damage than other products. Potential hazards are limited, though responsibility exists for any losses or damages, and threats mainly stem from natural disasters or terrorism. Pipeline transport is thus a reliable and efficient system for distributing certain types of cargo. Most commonly, pipeline systems are used in their basic form for transporting water, domestic gas, etc., as part of end-user supply for households and businesses.

Maritime Transport is vital for globally connecting markets and transporting large quantities of goods across intercontinental distances at low per-ton costs. It enables efficient movement of raw materials like oil and grain, as well as containerized products. Ships are tailored to specific needs; oil tankers carry liquids, while container ships are designed for standardized intermodal transport units. As ship sizes have increased over the years, the relative transport costs have decreased. However, maritime transport faces challenges. Adverse weather such as storms can affect reliability and speed, while larger ships require deeper ports, leading to higher infrastructure investments. Problems also arise from major events that can paralyze maritime routes (e.g., the Suez Canal blockage in 2021 or the 2024 Red Sea traffic disruptions due to attacks), as well as port capacity limitations, particularly in net importing regions. Despite these challenges, maritime transport remains the backbone of global distribution, connecting the entire supply network and enabling intercontinental trade. For optimal functioning, integration with other modes such as rail and road is necessary, ensuring smooth flow of goods from origin to final destination.

3 The Role of Distribution in Business Performance and Market Placement

Optimally and efficiently designed distribution channels help reduce complexity in other segments of the supply chain. According to Ross (2015), these channels may include the following functions:

- Assortment: Distributors group related or similar products into assortments to meet consumer preferences. For example, an auto parts distributor might assemble various components needed for brake repair into one package.
- Allocation: This function involves dividing large inventories of goods into smaller units or packages for sale. For example, a distributor dealing with construction materials might order large quantities of screws and then divide them into smaller packages.
- Sorting: This is the process of classifying various types of goods acquired from multiple suppliers into similar categories. For example, a fruit distributor might sort apples by quality and size.
- Accumulation: Here, the distributor gathers similar products into larger batches to offer them as a single unit. For instance, a distributor of electronics might bundle TVs of different brands into a common offer or group together products typically bought in combination, such as various computer components.

Distribution channels encompass essential services that are vital to the efficient functioning of the supply chain. Sales and promotion are crucial for manufacturers who often face challenges in market access due to limited sales outlets. To overcome these challenges, they often integrate distributors into their network. Additionally, distributors increasingly engage in converting semi-finished goods into final products through sorting, labeling, and simple assembly tasks. The transport of goods is essential to ensure that products arrive at the right place at the right time—failure to do so leads to lost sales and consumer distrust. Warehousing serves as a buffer between the uncertainties of supply and demand, ensuring sufficient inventory to meet consumer needs. Some distributors also perform sequencing, sorting goods into specific configurations tailored to customer needs, or assembling kits for lean manufacturing.

Many companies use traditional accounting systems to track costs, but these are often too generic for detailed analysis. To measure performance effectively and understand distribution operations, more granular cost data is needed. According to Rushton, Croucher, and Baker (2017), distribution costs can be broken into:

- Storage and warehousing costs: These include construction, labor, and equipment costs. Factors such as location, building age, and loading systems affect cost ratios. The size of the distribution center impacts per-unit costs—larger centers typically have lower unit costs due to better space and equipment utilization.
- Transport costs: These can be divided into primary transport costs (moving goods) and delivery costs (transport to the end consumer). Requirements and costs vary with the number of distribution points. Primary transport generally involves bulk shipments, while final delivery, which serves individual consumers, may be handled by third parties (3PL).
- Inventory holding costs: These include inventory management expenses, such as financing inventory, service costs like administration and insurance, and risk costs arising from theft, spoilage, and obsolescence.
- Information system costs: These relate to the need for data and communication, ranging from order to fulfillment. Costs increase with the number of warehouses in the system, as more complex information systems are required for effective management.

4 Distribution Strategies and Distribution Channels

A distribution strategy defines how goods or services reach end consumers. Choosing an effective distribution strategy is crucial for maximizing profit and maintaining customer loyalty.

- Strategies typically focus on distribution channels, which include:
- Indirect distribution: Goods pass through multiple channels before reaching the consumer.

- Direct distribution: Companies deliver goods directly to the consumer.
- Intensive distribution: Aims to achieve the widest possible market share.
- Selective distribution: Limited to specific sales points, as seen with brands like Zara.
- Exclusive distribution: Specific distributors receive exclusive rights for certain areas, e.g., Ferrari in a specific region.

The choice of distribution strategy often depends on the type of product. Companies may use different strategies for different products. A distribution network consists of channels and hubs that facilitate the transfer of goods. A distribution channel refers to the methods and means of moving goods from the manufacturer to the end point. The end point is usually a retail store, but with the rise of online shopping, home delivery is becoming increasingly significant. For digital products such as music and movies, "physical" delivery can occur via the internet.

Figure 5.2 illustrates the main alternative distribution channels for consumer goods from production to retail stores.

There are also other channels, such as those from industrial suppliers to customers or direct channels to the final consumer. Distribution channels from the manufacturer to retail stores can include:

- The manufacturer delivers goods to the retailer’s distribution center, which then sends them to the retail store.
- The manufacturer sells goods to a wholesaler, who then delivers them to the retail store.
- The manufacturer ships goods directly from its warehouse to the retail store.
- The manufacturer sells goods to an intermediary, who then delivers them to the store.
- The manufacturer uses small parcel carriers to deliver to retail stores.
- The manufacturer delivers goods via a cash-and-carry system for smaller retailers.
- The manufacturer uses third-party services (3PL) to distribute to retail stores.
- The manufacturer delivers goods directly from production to the retail store.

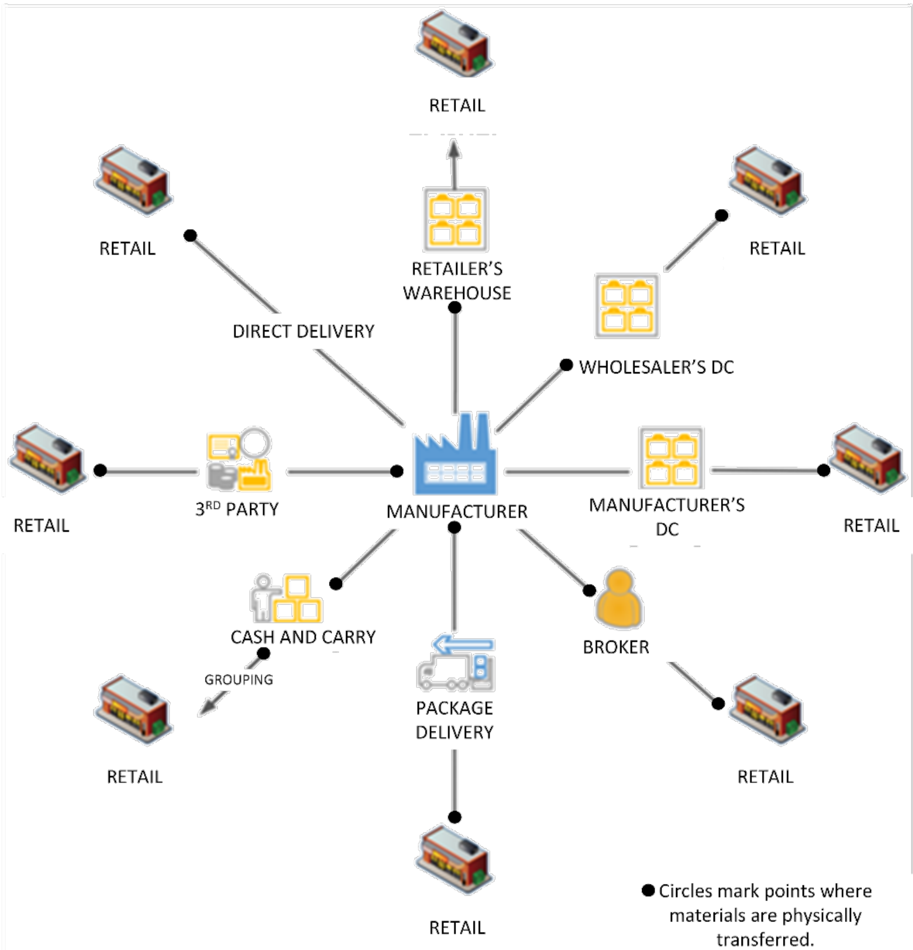

Figure 5.2: Alternative Channels for Distributing Consumer Goods to Retail Stores
Source: Adapted from Rushton, Croucher in Baker (2017)

In addition to the channels described above, there are also variants that do not involve retail stores, essentially representing flows referred to as B2C (Business-to-Consumer), where the manufacturer sells its products and services directly to the end consumer.

– Mail order is a popular method of purchase, where goods are ordered via a catalog and delivered directly to the consumer's home, bypassing the store.

- Direct delivery from the manufacturer to the consumer's home is rare, typically occurring after direct advertising sales or for custom-made products.
- Online shopping has become common, with additional specialized operations for home delivery, mostly carried out by 3PL companies, while some products are distributed directly online.
- The factory-to-factory or B2B channel is key for the distribution of industrial products, which include a variety of product types and sizes, and the transport may be handled by manufacturers or 3PL companies.

The structure of distribution channels varies significantly between companies. According to Rushton, Croucher, & Baker (2017, p. 56), basic variations include:

- The diversity of intermediaries or distributors,
- The number of stages in the distribution process, determining how many intermediaries are involved before the product reaches the consumer,
- The level of distribution intensity at each stage, determining whether multiple types of intermediaries are used at all levels, or only selective ones.

Some small and medium-sized enterprises (SMEs) often opt for simpler channel structures that allow for efficient and cost-effective distribution of their products. In contrast, large companies that offer a wide range of products and target diverse consumer segments typically have more complex distribution channels. In this context, it is worth mentioning that some companies follow a policy of disintermediation, attempting to eliminate certain intermediaries or middlemen to reduce costs and speed up market entry. For some companies, especially large ones, eliminating intermediaries becomes a crucial part of their supply chain strategy. However, due to the diverse needs and strategies of companies and the numerous variable factors, it is difficult to define a "typical" distribution channel.

5 Choosing a Distribution Strategy Based on Network, Market, and Products

When establishing distribution channels, several key objectives arise. The first goal is to ensure the correct market presence of products, meaning products must be made available to consumers at the right time and place. The second goal is to increase sales opportunities, achieved through strategies such as product positioning in stores and special promotions. The third goal involves participating in the determination of distribution factors, such as minimum order sizes, transport unit loads, and delivery time windows. The fourth goal is to maintain service levels through contractually defined standards, which ensure high service quality for customers. The fifth goal is reducing logistics operations and distribution costs, including optimizing resources and eliminating unnecessary operations. The sixth goal is to ensure an efficient flow of information, including sales trends, inventory levels, costs, and other data from sales points, which enables better management of the distribution system.

When designing a distribution system, it is important to consider various channel characteristics, including market, production, and competitive factors. These features influence decisions in planning an effective channel for distributing goods to end consumers. For example, the size and dispersion of the market, as well as the competitive landscape, will influence the choice between "long" channels, involving more transfers and warehousing, and "short" channels, better suited for smaller markets with limited consumers. This ensures the distribution channel aligns with the needs of both the market and the product.

Looking at the final part of distribution channels–typically from distribution centers (of either the manufacturer or the distributor)–we generally identify three main types of channel structures, based on how consumers order, from where, and how delivery is executed. These channel forms, illustrated in Figure 1.3, include:

- Single-channel distribution involves selling and distributing products through only one channel, either digital (e.g., an online store) or physical (e.g., a street retail store). This approach helps reduce costs as it is easier to manage and can sometimes be operated without third-party providers. It also allows businesses to focus on improving performance within one channel, which is especially useful when resources are limited, and no large management team is needed. Distribution follows the sales system–for instance, online sales typically rely on parcel delivery services.
- Multi-channel distribution enables sales and communication (and subsequently, distribution) through various channels such as telephone, website, social media, mobile apps, and physical stores, which operate independently. This means the

company may not have insight into the customer's previous interactions across different channels, as they function independently. Benefits of multi-channel commerce include reaching customers in diverse ways, comparing the effectiveness of each channel, and increasing brand awareness. Separate distribution methods are established for each channel–for example, the same product may be distributed via parcel delivery for online orders and stocked in a physical store.

– Omnichannel distribution combines multi-channel retail with integration across all channels, enabling a centralized view of operations and customer data. For customers, this provides a seamless shopping experience. Benefits of omnichannel distribution include leveraging the advantages of multi-channel systems, smoother transitions for customers between channels (which can boost sales), and more informed marketing decisions based on unified data. From a distribution perspective, this means centralized inventory management, greater flexibility, and allowing consumers to choose the distribution method that suits them best.

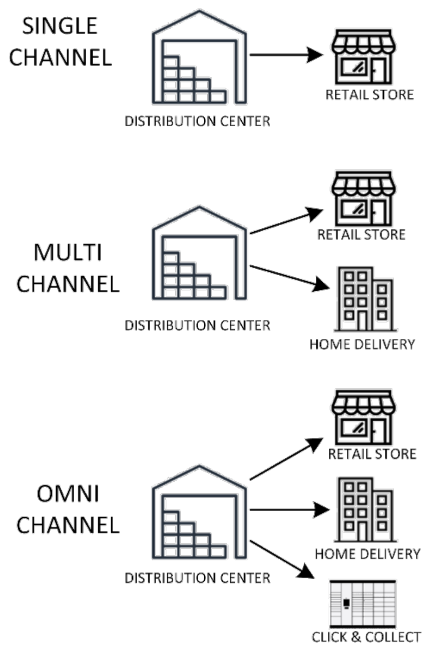

Figure 5.3: Types of Distribution Channels

Source: own source

When selecting a distribution channel, it is important to consider the nature of the product itself, as this can greatly influence the number and type of suitable channels (Rushton, Croucher, & Baker, 2017). For instance, high-value goods are more suitable for direct sales through short channels, as higher gross margins can more easily cover the increased sales and distribution costs typically associated with these channels. Furthermore, short channels are appealing due to enhanced security for high-value goods, as there is less risk of loss or theft. They also help reduce the need to hold large inventories of valuable goods, minimizing issues such as high working capital and obsolescence costs. On the other hand, complex goods, such as machinery, often require direct sales, since intermediaries may lack the expertise to adequately explain their function to potential consumers. New products are often best distributed through third-party channels, as final demand is difficult to forecast, and distribution channels must remain flexible to respond to varying demand levels. Time-sensitive goods, such as food, require faster or shorter distribution channels due to their limited shelf life. Goods with specific handling requirements–like frozen food, porcelain, glass, and hazardous chemicals–may require specialized physical distribution channels. Pharmaceuticals form a distinct category, requiring specialized channels and compliance with strict transport conditions.

Competitive characteristics relate to the activities of competitors selling similar goods. This includes decisions about whether to sell alongside competitors' products or use exclusive sales channels to avoid competition. In some cases, offering a wide range of products at the same retail locations is necessary if consumers demand it. It is also crucial to compare service levels with those of competitors and ensure equal or superior service, which can be a key competitive advantage–especially for goods where it is hard to differentiate based on quality and price.

The structure of goods distribution is generally either single-tier or multi-tier. The chosen structure depends on various factors such as the type of area (e.g., urban, suburban, rural), the size of the area (e.g., countries, continents), the type of goods being shipped, vehicle types used, and requirements for volume and time.

There are two main distribution methods: direct delivery–where goods are delivered from manufacturer to consumer without intermediaries or storage, giving the manufacturer greater control over branding and pricing, but incurring delivery costs to multiple locations–multi-tier delivery, where goods pass through a hierarchical structure of distribution centers, warehouses, and retailers before reaching the consumer, enabling faster availability but resulting in higher operating costs (Ross, 2015, p. 47). Both methods are commonly used depending on a company's production strategy. A single-echelon distribution structure (direct delivery) does not involve any intermediaries between supply and demand sources and operates through direct shipments—either from one source to one consumer or from one source to multiple consumers, as in consolidation. Conversely, a multi-echelon network includes intermediate facilities like warehouses, consolidation centers, distribution centers, and cross-dock systems where goods move from source to destination.

It is also essential to consider the challenges of transportation and fleet management when designing distribution (Bektas, 2017).

Distribution systems can be centralized or decentralized. In a centralized system, decisions for the entire supply chain are made centrally, resulting in smaller warehouse networks, minimal safety stocks, lower overhead and transportation costs, and the ability to achieve economies of scale and service targets at lower total cost. Decentralized systems face increased costs due to local inventory and transportation needs, leading to higher total costs. The key difference lies in delivery: centralized systems have longer delivery times due to greater distances, whereas decentralized systems offer shorter delivery times and lower costs as warehouses are closer to consumers (Ross, 2015, p. 47). Another advantage of decentralized systems is resource dispersion, which is useful in the event of a system failure, as another element can quickly take over the role.

The basic decision-making process for choosing a distribution strategy follows the same logic as other logistics decisions. This process is shown in Figure 1.4:

- First, a thorough analysis of the current situation is required, including identifying objectives, business strategy, the current distribution status, and the broader logistics strategy.
- Next, potential distribution options are identified—strategies, providers, target markets, and suitable methods.

– Then, the identified options are analyzed and evaluated based on distribution requirements and predefined priorities. Ideally, a decision model is created to evaluate all variants using specific parameters.
– Finally, the selected strategy is implemented, continuously monitored, and evaluated for effectiveness—and adjusted as needed.

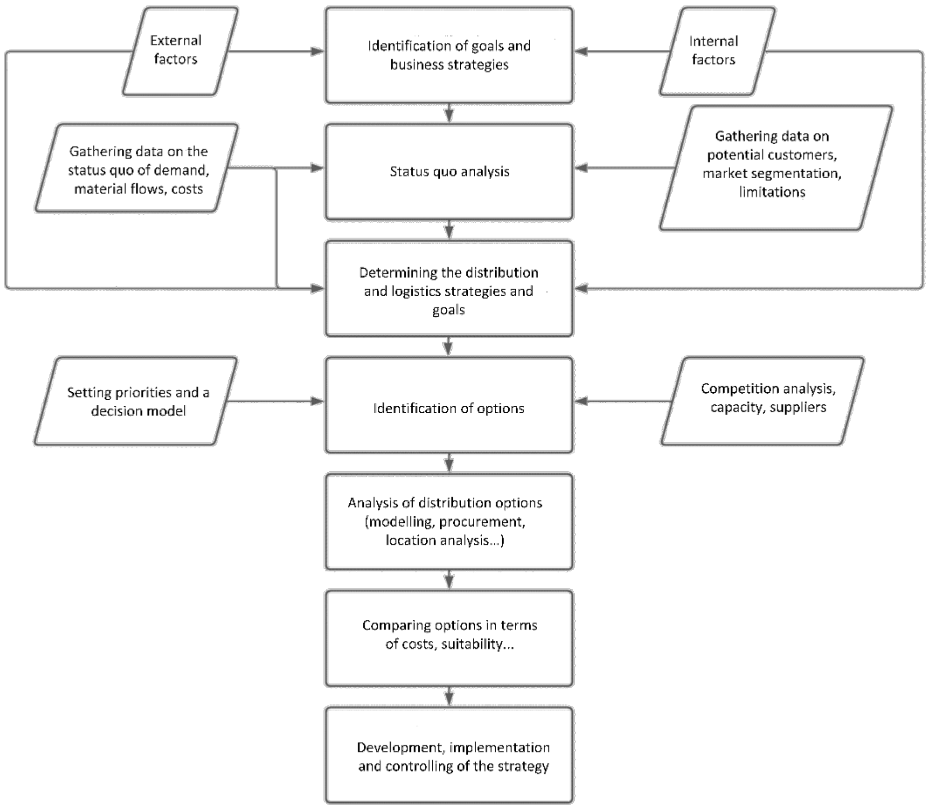

Figure 5.4: Decision-Making Process for Selecting a Distribution Strategy
Source: Adapted from (Rushton, Croucher, & Baker, 2017) and (Bektas, 2017)

Distribution is thus a crucial and at the same time challenging element of the supply chain, as it requires precise planning and strategic decision-making that directly affect a company's efficiency and competitiveness. The appropriate choice of a distribution strategy–tailored to the nature of the products, market conditions, and company goals–is essential for cost optimization, ensuring timely delivery, and achieving customer satisfaction. The complexity of distribution channels, involving various intermediaries and levels, necessitates thorough analysis and regular adjustments to enable a company to effectively respond to changes in demand and technological developments. Therefore, the design of the distribution network must be carefully aligned with broader logistics strategies and the development of the supply chains in which the company operates, thereby enabling long-term market success.

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DESIGNING HYBRID HUMAN-MACHINE WORKPLACES

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During the transition to Industry 4.0, workplaces are being transformed from manual through human-machine hybrids to automated, autonomous and smart ones. Each of the aforementioned designs represents a development challenge. A particular challenge is the development of hybrid workplaces, where using the potential of man and machine to the maximum extent possible is necessary. Lean principles are followed in designing workplaces and processes, reflected in the efficient use of time and minimized losses, as well as ergonomics principles. Due to the lack of labor force and the aging of the population, concern for maintaining employees' health is an important guideline for designing workplaces for the future. Knowing the basics of lean, time management and ergonomics while simultaneously learning about the computer environment for designing workplaces can be a good starting point for the prudent designing of the renovation of traditional workplaces into Industry 4.0 workplaces.

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1 Introduction

The introduction of digital technologies and automation in industrial environments–including collaborative robots (cobots), algorithms, artificial intelligence, the Internet of Things (IoT), big data, and cyber-physical systems (CPS) –is ushering in a new paradigm known as the Fourth Industrial Revolution (Cunha et al., 2022). This revolution is also referred to as Industry 4.0 (I4.0), Factories of the Future (FoF), or even Smart Manufacturing (Iordache, 2017; Gualtieri et al., 2020; Kadir & Broberg, 2021). Within this movement, interconnected or networked smart factories are envisioned, enabling efficient data collection and processing, automated management and operation coordination, and real-time operational monitoring (Moro et al., 2019; Çinar et al., 2021). Following this trend is expected to give companies a competitive advantage. But what does it mean to follow the trend? It involves transforming companies from novices to mature Industry 4.0 players. Part of this transformation includes reshaping traditional jobs that involve "repetitive tasks." Such jobs top the list for automation (e.g., Frey & Osborne, 2017) and productivity improvements through human-machine collaboration (Stern & Becker, 2019; Broday, 2020).

Equipped with new technologies, operators working on production floors will perform their tasks in cooperation with numerous technical innovations. In this context, the human operator–referred to in the literature as the "Operator 4.0"–is typically characterized by the technologies they use. For example, when using exoskeletons, the worker is portrayed as a super-strong operator or a healthy worker, as they utilize smart wearable solutions that collect psychophysiological data (Romero et al., 2016a; Ruppert et al., 2018). Some authors emphasize that new technologies, particularly exoskeletons and cobots, have the potential to improve productivity and workplace health (e.g., by preventing musculoskeletal disorders through reduced strain on the musculoskeletal system) (Cimini et al., 2020; Ranavolo et al., 2021). However, the mere use of technology does not guarantee reduced risk of musculoskeletal problems, as noted by Cockburn (2021) and Bounouar et al. (2022). There is also a belief that relieving workers from repetitive and monotonous tasks through technology could help enhance their skills–especially regarding system supervision. In this sense, it is expected that workers will become more skilled and autonomous as a result of technological integration (Romero et al., 2016a; Thun et al., 2019; Broday, 2020). Nevertheless, concerns remain that the adoption of new technologies may lead to increased employee surveillance (e.g., through sensor-based applications), intensified work, gender segregation, and reduced worker decision-making (Piasna & Drahokoupil, 2017; Moro et al., 2019; Beer & Mulder, 2020; Kaasinen et al., 2020; Kadir & Broberg, 2020; Golsch & Seegers, 2021).

The extent of the impact of technology-driven changes on workers' health and work is still largely unknown (Badri et al., 2018; EU-OSHA, 2018; Bobillier Chaumon, 2021; Zorzenon et al., 2022). Health challenges potentially arising from I4.0 include:

- Mental health concerns stemming from reduced autonomy and rising skill demands,
- Increased cognitive workload due to the use of automation technologies such as cobots and automated vehicles,
- Job insecurity linked to increased dependence on technology (Golsch & Seegers, 2021; Kadir & Broberg, 2021; Reiman et al., 2021).

Aligned with the concept of I4.0 as a "new industrial stage," research still predominantly focuses on the technical aspects of I4.0 transformations, rather than on human labor (Neumann et al., 2021; Barcellini et al., 2021; Bentley et al., 2021). The neglected social dimension of the I4.0 workplace includes working conditions, new work organization models, methods of worker-technology interaction, new constraints and resources introduced by technology, changing skill requirements, learning opportunities, or emerging risks that may threaten workers' health and well-being (Barcellini, 2019; Bounouar et al., 2022). According to Moniz & Krings (2016), these issues are often addressed only from the perspective of technical improvements and safety in relation to worker-technology interaction. Continued neglect of the social dimension of the I4.0 workplace in both theory and practice calls into question the success of I4.0 approaches and their impact on the people required to sustain them (Neumann et al., 2021).

In planning I4.0 implementations, it is necessary not only to focus on technology but also on the operators and their work activities. In addition to ensuring time-efficient operations, it is crucial to assess the risks to which Operator 4.0 will be exposed and the health impacts of their work.

2 The Concept of Operator 4.0 and the Status of Human Labor in Industry 4.0

The analysis of industrial transformation primarily anticipates the development of automation and self-management components, but it still relies on human presence. Instead of replacing humans with technology, the focus of Industry 4.0, according to many researchers (e.g., Cimini et al., 2020; Paliga & Pollak, 2021), is on relieving workers from strenuous and monotonous tasks and developing new skills that enable them to manage advanced and complex systems. The role of the worker, referred to as Operator 4.0, involves taking on newly configured activities within the work system. Currently, there are two visions for achieving this. The first envisions the human operator as empowered by technology and transformed into a "smart operator" through the use of smart technologies (Romero et al., 2016a). The second suggests that the operator may not be capable of handling all the demands posed by new technologies and will require training and reskilling to adapt to these changes (Li, 2022).

While literature continues to assume that humans will play a central role in managing Industry 4.0 systems, the definition of the operator remains blurred and is conceptually unified under one vision, described by Romero et al. (2016a, 2016b). According to Romero et al. (2016a), operators in Industry 4.0 are defined by the technological resources they use. They are classified into seven main typologies, which do not reflect different worker types, since multiple technologies can be used for the same job:

- Super-strength operator (using exoskeletons),
- Augmented operator (using augmented reality),
- Virtual operator (using virtual reality),
- Healthy operator (using smart wearables to measure physical activity),
- Smart operator (leveraging available smart technologies),
- Collaborative operator (working with cobots),
- Analytical operator (using and analyzing big data collected by the system).

According to this vision, smart factories are expected to harness not only the benefits and capabilities of smart machines through human-machine interaction, but also to empower their operators with new skills and tools (Romero et al., 2016a; Patriarca et al., 2021; Shi et al., 2021). These operators are expected to (1) have control over work processes and associated technologies, and (2) possess autonomy in developing their own skills. Therefore, Operator 4.0 is typically portrayed as an intelligent and skilled operator who uses technology according to their needs (Romero et al., 2016b; Kaasinen et al., 2020), or, in other words, an "industrial worker whose cognitive, sensory, physical, and interactive abilities are enhanced through interaction with Industry 4.0 technologies" (Gazzaneo et al., 2020, p. 221).

Gajšková et al. (2020) observe that I4.0 technology enables Operator 4.0 to decide independently–based on work circumstances–whether, how, and when to use the technology. For this reason, I4.0 is expected to transform work from repetitive, low-skilled, and physical labor into work that involves more complex and cognitive tasks, as decentralized decision-making grants workers greater autonomy. It should also be recognized that the more cognitive capabilities a task requires, the harder it is to claim that such tasks can be replaced by technology (Blštáková et al., 2020; Cimini et al., 2020; Golsch & Seegers, 2021). As work requirements become more complex, these systems may demand greater specialization, flexibility, and adaptability, increasing the need for qualifications and technical skills (Blštáková et al., 2020; Ivaldi et al., 2021). Mark et al. (2019) add that assistance systems can provide better opportunities for integrating and supporting workers with disabilities. Including these workers can enhance this potential and make the industrial sector a best-practice model within truly participatory and inclusive business environments.

These qualifications and technical skills are encouraged by work situations in specific contexts and develop through practice (Teiger & Lacomblez, 2013), rather than being acquired before such situations arise. Training can contribute to their development, but no universal learning or workplace training system exists. Research on digital learning environments is still emerging and mainly limited to demo applications (EU-OSHA, 2018; Engeström, 1999). On one hand, technology can create opportunities for new forms of on-the-job training, such as digital work instructions or virtual training (Hoedt et al., 2020; Chistyakova et al., 2021). On the other hand, training is more effective when it integrates real work situations and everyday use of technology (e.g., Galey et al., 2020).

The concept of Operator 4.0 remains vague, as does the status of human labor in the conceptualization of Industry 4.0 work scenarios, which continue to be overshadowed by assumptions of fully capable, healthy, young, gender-neutral, and highly skilled workers. In practice, however, many risks and negative effects of Industry 4.0 for workers are already emerging. Some of these are discussed in the following chapters (Cunha et al., 2022).

2.1 Risks and Impacts of Industry 4.0 on Health

The relationship between humans and technology is established within a specific context, influenced by a particular form of work organization. This means that technology is neither universal nor transferable from one environment to another without consequences for the activity carried out within that environment. Therefore, rather than merely identifying risks caused by technology, it is more important to understand them within the specific contexts in which they occur (Adriaensen et al., 2019).

Although automation has led to a reduction in manual labor, this does not mean that physical risks have been entirely eliminated from the workplace. Automated devices can also pose mechanical and electrical hazards, including noise, vibrations, and exposure to chemicals or radiation (Leso et al., 2018; Hoyer et al., 2020; Costantino et al., 2021). Additionally, less tangible risks–particularly psychosocial ones–often remain invisible (Badri et al., 2018; Bobillier Chaumon et al., 2019; Costantino et al., 2021). These include irregular work schedules (e.g., 12-hour shifts) due to continuous, automation-driven shift operations (Cunha et al., 2020), increased pressure to work at the pace of cobots, and heightened work surveillance through monitoring and tracking systems. Such working conditions negatively affect both physical and mental health and may manifest as musculoskeletal disorders, technostress, or anxiety (Valenduc & Vendramin, 2016; EU-OSHA, 2018; Ghislieri et al., 2018). These impacts can also present as physical pain or psychological distress. Health deterioration can be prevented by monitoring and addressing risk factors. The rise of robotics may increase isolated work and reduce contact between colleagues, contributing to workers' perceptions of losing control over their professional practices and the shared standards for quality and healthy work (Bobillier Chaumon et al., 2019).

While new technologies can enhance the value of work, they may also constrain workers' activities through (1) increased prescription of tasks and (2) reduced operational autonomy. In this way, workers are not allowed to apply their professional knowledge and experience to achieve well-executed work, which is key to workers' identity and a foundation of mental health and well-being at work (Bobillier Chaumon et al., 2019). As Thun et al. (2019) note, the advancement of automation could jeopardize workers' autonomy.

Many Industry 4.0 studies have focused solely on the technical aspects of design, often ignoring or only partially considering the social relations they support (Sony & Naik, 2020). Since even physical issues such as musculoskeletal disorders are linked to organizational and psychosocial factors, their prevention cannot be analyzed independently of the context and the relationships within it (Coutarel et al., 2022). As a result, overlooking these contextual features can perpetuate negative effects for workers (Barcellini, 2019). In a qualitative study by Kadir and Broberg (2020), based on interviews with 15 workers and 20 decision-makers from 10 companies that recently introduced digital technologies, several factors were revealed that influence well-being and performance. These included knowledge of how new systems operate, employer support, job security, and both physical and cognitive workloads associated with using the technology. Furthermore, workers expressed concern about "causing errors or damaging expensive digital systems," particularly when they were not properly trained in their use.

Research in occupational psychology and activity ergonomics consistently highlights the essential role of participatory approaches in addressing such risks (Béguin & Cerf, 2004; Barcellini et al., 2015; Bobillier Chaumon, 2021). Nevertheless, many studies still focus on the potential of technology. For example, in the study by Gualtieri et al. (2020), a manual assembly station was redesigned as a collaborative one (with cobots) based solely on a physical ergonomic assessment and productivity gains.

Including workers' perspectives in design processes provides insights available only to those performing the work, as their views are grounded in real-world knowledge of daily operations (Rangraz & Pareto, 2021). In connection with innovation models that promote sustainable leadership and communication at work (Iqbal et al., 2021), involving workers in the design process fosters trust between workplace actors. This approach also allows workers to see how their work is valued and how it contributes to organizational success (Saabye et al., 2020; Rangraz & Pareto, 2021).

Despite the foundational goal of Industry 4.0 to use technical innovation to place humans at the center again (see Saraceno, 2020), human and technical aspects have been unequally perceived–on the assumption that operator adaptation to technology is essential for the reliable functioning of work systems. Nonetheless, the importance of the human operator in Industry 4.0 contexts now appears to be recognized in the literature (e.g., Fantini et al., 2020; Pacaux-Lemoine et al., 2022). Human involvement remains essential in environments characterized by heterogeneous technologies (e.g., cobots, exoskeletons, cyber-physical systems) (Barcellini et al., 2021). Beyond ensuring safe and effective interfacing between multiple technologies, the operator contributes to system reliability–for instance, by reconfiguring processes during unexpected events, managing task variability, and anticipating potential consequences of irregularities.

Current definitions of Operator 4.0 do not clarify whether the concept is gender-neutral and, if so, how changes in work and organization affect existing (or create new) gender inequalities, or how gender segmentation is intertwined with technological development in the Industry 4.0 era. Cunha et al. (2022) found that gender segregation persisted even after automation was introduced, acknowledging that such segregation is not independent from the historical knowledge of manual labor acquired by different generations of workers. In short, technology interacts with gender and has yet to be independent from it.

The aging workforce, expected to continue growing, poses a threat to the long-term sustainability of new Industry 4.0 work systems (Brozzi et al., 2020). With a large number of older workers likely to remain active longer, the need for safer work, accessible lifelong learning, and inclusive employment becomes increasingly clear (Gaudart, 2016). Some authors argue that Industry 4.0 offers advantages in this regard, as its systems automate physically demanding, repetitive, and monotonous tasks (Brozzi et al., 2020; Agnusdei et al., 2021). However, the learning demands of I4.0 systems are likely to favor new (possibly younger) workers who are “better equipped to learn” (Badri et al., 2018, p. 407). Moreover, simply introducing new technologies does not ensure that workers’ needs for job stability and security will be met (Longo et al., 2020). On the contrary, increasing work intensity, the constant need to adapt to specific production demands–"which do not follow the same rhythms, demands, or goals" (Gaudart, 2016, p. 16)—and irregular work schedules (e.g., Cunha et al., 2020; Rangraz & Pareto, 2021), may undermine the sustainability of these new work systems.

2.2 Research Opportunities

Case studies involving workers as key participants, followed by an analysis of the health and well-being impacts of Industry 4.0-related work reorganization, are a necessary step for future research. This is particularly important as experience with these technologies still needs to be developed to better understand emerging risks related to work-related illnesses. In line with the Sustainable Development Goals (United Nations, 2020) and the findings that the Operator 4.0 is not a gender-neutral worker–and that work affects women and men differently (e.g., Messing & Silverstein, 2009) –gender dimensions must also be integrated into future research investigating such impacts, in order to promote healthier (Goal 3), more equitable (Goal 5), and more sustainable jobs (Goal 8). The key question, then, is: How can Industry 4.0 technologies serve as a driver for achieving these goals? (Cunha et al., 2022)

3 Simulation of Human Labor, 3D Production Planning, and Virtual Ergonomics with ema Work Designer Software

According to Spitzhirn et al. (2022), planning and designing production and work systems requires a holistic approach that considers both levels of planning–factory-level and workstation-level. Currently, separate digital tools are predominantly used for factory layout planning and detailed workplace system planning. This often results in workers being inadequately or insufficiently considered during the production planning process. Consequently, costly and time-consuming redesigns may be required to resolve problems in existing production and work processes.

Using the case of a washing machine assembly, an iterative approach is presented for digitally supported combined planning at both the factory and workplace levels. The overall design of the assembly line can be carried out using the ema Software Suite, which includes ema Plant Designer (emaPD) and ema Work Designer (emaWD). In the case study, emaPD is used to optimize production elements such as operational resources, layout, and logistics, considering material flow, lead times, and production costs. A simulation environment is used for detailed workstation-level planning with emaWD, which applies an algorithmic approach to autonomously generate human movements based on objective task descriptions.

The generated simulations are reviewed and optimized using production time evaluation (MTM-UAS) and ergonomic risk assessments (EAWS, NIOSH, reach-and-vision), as well as worker capabilities (e.g., age, anthropometry). This enables the design of an efficient factory with optimized material flow, minimized production costs and lead times, while considering spatial constraints and ergonomic factors. Ergonomically unfavorable tasks can be taken over by robots in hybrid workstations, thereby improving workplace ergonomics. This digital planning approach combining factory design (emaPD) and workstation planning (emaWD) enables early, coordinated, and efficient design of both cost-effective and ergonomically sound production systems.

3.1 Challenges in Designing Cost-Efficient and Ergonomically Suitable Factory and Work Systems

According to Spitzhirn et al. (2022), increasing cost pressure from competition, labor and material costs, greater product diversity, shorter product lifecycles, and rapid time-to-market cycles demand that production and work systems be planned and restructured more quickly and frequently (Spath et al., 2017; Bracht et al., 2018). In planning and designing production and work systems, factors such as cost, time, quality, time-to-market, and flexibility must be considered–alongside ergonomic workplace design and the allocation of labor based on skillsets (Schenk et al., 2014; Schlick et al., 2018).

Factory or production planning and work system planning typically involve different departments. At the factory planning level, focus is placed on production programs, space allocation, and the design of the factory and production systems. Work system planning involves workstation and process design–such as equipment layout and human-machine/robot interaction–according to economic and ergonomic criteria. While early, coordinated, and efficient factory, production, and workstation planning is crucial, it is often not carried out with sufficient accuracy (Bracht et al., 2018).

Many companies use digital tools for factory and workstation simulation and planning (Wiendahl et al., 2015; Bracht et al., 2018; Burggräf et al., 2021). Available software increasingly includes features like Integrated Factory Modeling (IFM), which offers more detailed insights than simple 3D visualization (Burggräf et al., 2021). However, separate tools are still often used for factory/logistics planning and detailed workstation planning (Bracht et al., 2018). These tools differ in terms of functionality and usability, they do not share a common database. As a result, data conversion into compatible formats is required, which is time-consuming and may lead to data errors or loss.

Using two or more software tools requires significant investment from companies and skilled experts who can operate multiple systems. Training these experts is costly and time-consuming. Moreover, not all tools offer interfaces for integration with other software, which leads to separate planning processes for the factory and the workplace. This can result in costly and time-consuming redesigns when solutions optimal in one tool prove suboptimal in the other. For the design and planning of factories and work systems, it is therefore reasonable and efficient to use a single software platform and a holistic approach that integrates both factory-level and workstation-level planning. This reduces planning costs, improves outcome quality, and minimizes the planning effort.

The following sections present an iterative approach to continuous digital planning between factory and workstation levels using the EMA software tool suite.

3.2 Digital Factory and Work Planning for Cost-Effective and Ergonomically Designed Production

Using the case of a production and assembly planning project for a washing machine, this section describes an iterative, combined approach to factory and workplace planning using the EMA Software Suite (Spitzhirn et al., 2022). The goals are to redesign the assembly line and optimize the production line. It is also necessary to evaluate whether the planned production program can be realized with the existing machinery and assembly capacity, and how to improve the overall economic efficiency of production while ensuring favorable ergonomic conditions for workers at individual workstations.

Based on the production program and product assortment, target quantities, planning period, and both quality and quantity requirements must be defined. The product itself must also be examined, as its components determine manufacturing processes, handling technologies, etc., while the product structure dictates the assembly sequence. Product modifications, such as simplifying or merging functional units, can affect technical, economic, and ergonomic conditions (e.g., weight, force, grip type) of production (Schenk et al., 2014; Bracht et al., 2018).

The washing machine consists of 86 components, including the frame, drum, drain pump, various hoses, pipes, and screws. These parts vary in shape, dimensions, and weight. The total weight of the washing machine is 82.95 kg, with component weights ranging from a few grams to over 10 kg. The product is manufactured in three color variations: white, blue, and orange.

The functionalities of the EMA software are illustrated through EMA Plant Designer (emaPD) and EMA Work Designer (emaWD). Both systems can be used independently or integrated into a single interface. Factory-level production and assembly planning is conducted using emaPD (macro-level), while detailed 3D visualization and workstation-level planning—addressing economic, temporal, and ergonomic criteria–is handled in emaWD (micro-level). Planning data can be exchanged directly and synchronously exchanged via a bidirectional interface between emaPD and emaWD.

Computer-aided modeling, analysis, and optimization of production is conducted in emaPD using mathematical and analytical methods (e.g., queuing theory per Manitz, 2008), factoring in lead times, spatial requirements, and production costs. Required input data include product details (planned quantities, bill of materials, batch sizes), process data (technological steps, packaging data), and resource data (availability, costs, area, number of shifts).

The first step is to assess whether the production goal (80,000 washing machines annually) is achievable under current conditions (e.g., number and types of machines). Bottlenecks, spatial requirements, or critical production paths can be identified to determine improvement actions (e.g., adding machines, buffer zones, shifts).

Further decisions must address in-house vs. outsourced production, machine types and equipment, and the macro-level work processes. emaPD can be used to create alternative machine setups and technological processes, simulating production scenarios while considering cost, resource availability, space, and production time. To analyze potential issues related to space, ergonomics, and timing for workers, emaPD results can be exported into emaWD. Interaction between a human operator–represented by a digital human model with customizable traits–and the workstation can be evaluated in emaWD. If results are unfavorable, workstations or tasks can be adjusted for ergonomic and economic improvements.

The Overall Equipment Effectiveness (OEE) can be calculated in emaPD to evaluate productivity and machine-related losses. Material and manufacturing costs can also be computed in emaPD, including storage, machine (hourly or fixed/variable), and purchased parts costs. When used alongside emaWD, investment costs for equipment can also be considered, influencing overall production costs. Production and assembly times in emaWD can be measured or estimated using the MTM-UAS standard time method.

emaPD evaluates total production capacity across all machines and factory space, not just individual workstations. Different workstation layouts and process variants can be simulated and assessed using Key Performance Indicators (KPIs) such as space requirements, production volume, and cost. Detailed workstation layouts and equipment placement within them can be designed in emaWD and exported to emaPD, enabling material flow optimization based on transport intensity and effort. The planning process can also integrate physical workload data. Standard machines and workstations created in emaPD can be imported into emaWD for 3D modeling.

Detailed workstation planning and design are carried out in emaWD using anthropometric human models–from small women to tall men with different capabilities (including age-related flexibility and strength)–to design efficient, ergonomic, and capability-based workflows (Ullmann & Fritzsche, 2021). The human model configurator allows users to add models into the 3D environment.

Manual and semi-automated tasks and human-robot interactions can be simulated in emaWD. The path and motion of the digital human model are generated automatically based on parameterized activity descriptions (using the task library in the ema simulation environment) and definitions of basic working conditions (e.g., objects to be handled, target positions, etc.).

Users can apply a variety of established analysis methods, including standard time estimation using MTM-UAS (Bokranz & Landau, 2012), walking distance, value-added activity percentage, health risk assessment via EAWS (Ergonomic Assessment Worksheet) (Schaub et al., 2012), and the NIOSH lifting index (Waters et al., 1994). These analyses in emaWD help identify economic and ergonomic issues (Fritzsche et al., 2019b; Spitzhirn et al., 2022). Improvements can be implemented by adjusting the work environment (e.g., table height), transferring harmful tasks to robots, or redistributing tasks across workstations. The final scenario is documented in the EMA suite using reports, images, videos, and production process simulations.

3.3 Results of Iterative Digital Production Planning Using Digital Factory and Workplace Design

A total production volume of 80,000 washing machines is planned, distributed across three color variants (white: 55,000, blue: 15,000, orange: 10,000). Figure 3.1 illustrates example outputs obtained using the emaPD tool, specifically for the washing machine production scenario.

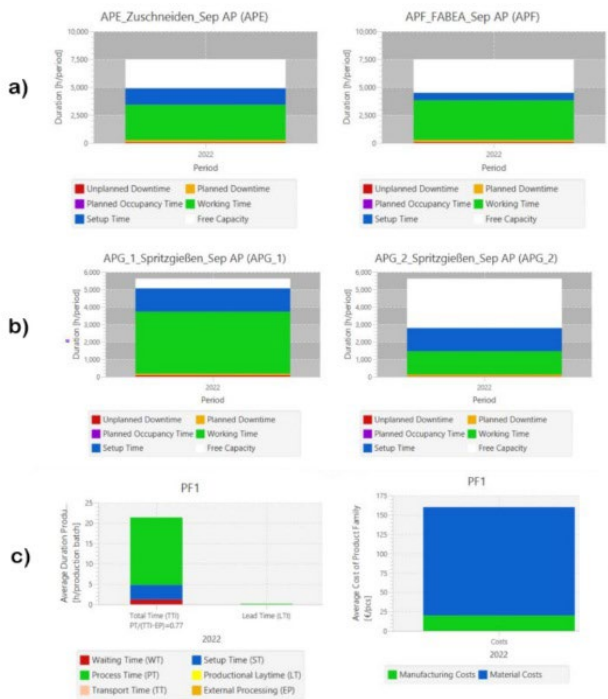

Figure 3.1: Examples of Results in emaPD for Washing Machine Production

Source: own source

Considering machine availability, delivery costs, lead times, and resource constraints, 23 components are produced in-house, while 63 are purchased. The simulation of the current production state showed that the system is unable to fulfill the entire order volume, with a shortfall of 7,587 units. By increasing the number of cutting machines from two to three, adjusting and synchronizing batch sizes, and optimizing execution times (e.g., reducing wait times, redirecting orders to less busy machines), the required production volume was achieved.

On the assembly line, which consists of eight connected workstations with a total of 14 employees, blocking times at station APB were reduced from 348 hours to 180 hours, and at station AP1 from 133 hours to 60 hours. Downtime at AP1 was also eliminated (reduced from 86 hours to 0 hours) by introducing five buffer zones between APB and AP1 and eight buffer zones between AP1 and AP2. The production area covers 530.06 m², generating production costs of €159.98. Utilization rates vary by workstation–from 98.6% on the assembly line to 48.6% on injection molding machine type A.

Following rough planning, the factory layout and assembly line were transferred from emaPD to emaWD. In emaWD, the material flow was refined, including path networks and layout simulations. Additional elements such as conveyors, shelves, and boxes were added, along with necessary input data (e.g., weights, masses, and exact layout coordinates) for ergonomic and time assessments.

Analysis of current assembly workstations using an average male digital human model showed 4 red, 7 yellow, and 3 green workstations according to the EAWS ergonomic assessment. Red and yellow ratings indicate increased risk for musculoskeletal disorders. An ergonomic assessment was also conducted based on worker age. For this purpose, the simulation model was supplemented with additional human models:

(1) a short, older woman (age group: 60; 154 cm; reduced age-related mobility),

(2) a tall young man (age group: 20; 194 cm; age-appropriate mobility and strength),

(3) a tall older man (age group: 60; 183.5 cm; reduced mobility and strength due to age).

The feasibility test showed that a medium-sized man, a tall young man, and a tall older man can perform all production activities. However, the shorter older woman was unable to reach all required locations on the washing machine assembly conveyor. A visual summary can be generated to show tasks that the shorter elderly woman cannot perform. For example, a woman around age 60 would likely be unable to push the drum into the washing machine frame (workstation 1R), which also affects station 1L, where both operators fasten the drum together.

Human differences in anthropometry, flexibility, and maximum strength also affect workload assessment and biomechanical risk scores per EAWS. Table 3.1 shows that physical workload per EAWS at workstations 1R, 2R, and 4L is higher for the short, older woman compared to the middle-aged man and the older man. Additionally, as shown on Table 3.1, task feasibility is limited or infeasible at stations 1R and 4L due to short stature and age-related mobility limitations (Spitzhirn, 2017).

Table 3.1. Summary of Ergonomic Test Results Based on Feasibility Testing and EAWS for Workstations 1R, 2R, and 4L

	Workplace 1R			Workplace 2R			Workplace 4L		
	M50-AK40	F05-AK60	M95-AK60	M50-AK40	F05-AK60	M95-AK60	M50-AK40	F05-AK60	M95-AK60
Feasibility	YES	NO	YES	YES	YES	YES	YES	NO	YES
= EAWS points [1]	61,5	(70,0) [2]	68,5	52,5	56,5	52,5	59	(63) [2]	37
+ points due to limb position	6	(5,5)	7,5	2	2	2	24	(28)	2
+ points due to forces	50	(59)	56	34	34	34	33	(33)	33
+ points for working with loads	-	(-)	-	16,5	20,5	16,5	-	(-)	-
+ extra points	5,5	(5,5)	5,5	-	-	-	2	(2)	2

[1] Legend: EAWS (high health risk > 50 points, potential health risk > 25 points, low health risk ≤ 25 points)
[2] not feasible based on feasibility check with emaWD
Source: Adapted from Spitzhirn et al., 2022

To improve ergonomic and economic outcomes, several corrections and enhancements were made to the simulation model. These measures were subsequently simulated in emaWD and evaluated using EAWS and MTM-UAS methods. The implemented improvements were as follows:

- A Fanuc CR35ia robot, capable of lifting up to 35 kg (washing machine drum = 30.7 kg), was introduced at workstation 1R (handling the drum), reducing the EAWS score from 61.5 to 23 points.
- A UR10e robot was added at workstation 2R (handling the rear panel), reducing the EAWS score from 52.5 to 32 points.

- A pedestal was introduced at workstation 4L (EAWS score reduced from 59 to 31.5) and at workstation 5L (EAWS score reduced from 40.5 to 40.0).
- The relay assembly task was moved from workstation 3L to 7R, improving ergonomics and balancing the line (EAWS score reduced from 55.5 to 42 points).

After reconfiguration, the cycle time was reduced from 70 to 60 seconds based on MTM-UAS, and workstations were time-balanced by reallocating tasks between them.

The optimized model data were transferred back from emaWD to emaPD. Due to workstation balancing and other improvements, the buffer capacity was significantly reduced—only the buffer between APB and AP1 was retained. Downtime on the conveyor was reduced to less than 50 hours, and production costs decreased by nearly 10%, while output increased.

4 Conclusion

The chapter *Designing Hybrid Human-Machine Workstations* defines the core concepts needed to understand a highly relevant topic in the era of digital transformation, Industry 4.0, and the push for sustainable operations. Employees are becoming Operators 4.0. Industry is not only facing a new technological revolution but also a fundamental change in working conditions, employee skill requirements, and qualifications.

As demonstrated, upgrading manual workstations to human-machine work environments must not focus solely on technology; it must also account for potential risks to employee well-being and health. This dual-focus facilitates smoother transitions to Industry 4.0, reduces resistance from workers, and results in more sustainable positive outcomes for both employees and companies.

The methods used to evaluate the economic and ergonomic value of workstations are not new—the novelty lies in how they are applied. Formerly done manually with pen and paper, today these assessments are performed using reliable digital tools. Results obtained with digital tools are fully comparable to traditional methods. One such tool, EMA Suite, was illustrated in Chapter 3, alongside methods such as EAWS, NIOSH, and MTM-UAS.

Comprehensive planning of hybrid human-machine workstations requires extensive knowledge of new technologies, logistics, process-based approaches, workplace ergonomics, time studies, lean methodology, sustainability, and digitization. We hope this contribution has demonstrated the need for a multi- and interdisciplinary approach to designing hybrid human-machine work environments. Rather than deterring practitioners, the scope of this challenge and the positive outcomes for workers and companies should encourage faster adoption of hybrid workstations in today's industrial settings.

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STRENGHTENING SUPPLY CHAINS: STRATEGIES FOR RESILIENCE AND AGILITY

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The higher education textbook " Strenghtening Supply Chains: Strategies for Resilience and Agility" is a comprehensive guide aimed at supporting resilience enhancement in supply processes and improvements within logistics operations. It emphasizes modern approaches and concepts for building resilience, strategies for procurement, distribution, ergonomic environment assessment, and educating on the interdependence of supply chain components, all while increasing added value and productivity through greater resilience and adaptability in logistics companies. This interdisciplinary approach combines knowledge from various fields—management, logistics, distribution, ergonomics, procurement, and human resource management. Readers are equipped with practical knowledge and skills to improve the resilience and adaptability of individual processes. Topics covered in the textbook include: 1) Strategies for Supply Chain Resilience; 2) Urban Logistics; 3) Increasing Awareness of the Importance of Supply Chains; 4) Strategic Procurement; 5) Smart Distribution; and 6) Workplace Ergonomics in Logistics. The entire content is directed toward strengthening resilience competencies essential for the green and digital transition of logistics companies and fostering a stronger EU economy based on resilient supply chains.

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