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Integration of Collaborative Robots in Manufacturing SMEs: Analysis of Productive and
Organizational Impacts and Development of a Decision-Making Model

TITLE in Italian

Integrazione dei robot collaborativi nelle PMI manifatturiere: analisi degli impatti produttivi e
organizzativi e sviluppo di un modello decisionale

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ABSTRACT

This thesis analyses the impact of collaborative robots on productivity and work organisation in manufacturing SMEs, situating the topic within the broader context of the competitive and technological transformations affecting contemporary manufacturing. The aim of the study is to understand how cobots may represent an automation solution consistent with the needs for flexibility, reconfigurability, and economic sustainability that are typical of SMEs, as well as to define a structured approach for assessing their integration. To this end, the research adopts a multi-method approach based on a literature review, an analysis of cases and applications documented in existing studies, and the development of a dedicated decision-making model.

The results show that the benefits associated with the use of cobots are not automatic, but depend on the correct selection of the task, the design of the cell, the balance between operational performance and safety constraints, and the organisation's ability to support the reconfiguration of work. The applications that appear most transferable to the SME context primarily concern pick-and-place and machine-tending activities, while, at the organisational level, a gradual reallocation of work emerges from executive tasks towards supervisory functions, quality control, and exception management. From an economic perspective, the convenience of adoption proves to be particularly sensitive to utilisation rates, production mix, actual annual operating hours, and reconfiguration times.

The main contribution of the thesis lies in the proposal of an operational decision-making model, structured according to a Gate + Scoring logic, capable of integrating technical, economic, and organisational dimensions, making assumptions and trade-offs explicit, and supporting a transparent comparison among integration alternatives. Although empirical validation is still lacking, the study proposes a conceptually robust model that is open to subsequent applications through simulation and/or case study, thereby providing manufacturing SMEs with structured support to guide

automation decisions that are more robust, traceable, and consistent with their work system.

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INTRODUCTION

Contemporary manufacturing is undergoing technological and competitive transformations that affect value creation models and the ways in which production processes are organised (Rullani, 2014). In this scenario, competitive positioning increasingly depends on the ability to combine efficiency, quality, and responsiveness to the market (Rullani, 2014). At the same time, the spread of the Industry 4.0 paradigm is associated with the integration of manufacturing technologies and information technologies, with significant implications also for SMEs (Ynzunza Cortés et al., 2017).

Within this context, collaborative robots (cobots) represent an automation solution oriented towards human-robot collaboration in close proximity and/or within the same operating space, according to a human-centred logic that integrates the capabilities of the robotic system with the adaptability of the operator (Galin & Meshcheryakov, 2019; Boschetti et al., 2023). The literature also highlights that cobots are designed to work directly with operators and to be more accessible in terms of use and interaction, also thanks to simpler programming and commissioning methods than those required by traditional industrial robotics (Santoni & Lucato, 2021; Polonara et al., 2024). The topic is particularly relevant for manufacturing SMEs, where product variety and frequent changeovers may make the adoption of rigid, highly specialised automation less sustainable; in such contexts, there is a need for more versatile solutions that are manageable even in the presence of limited resources and competences (Perzylo et al., 2019).

Since integration choices depend significantly on the type of process and on cell constraints, the application analysis is delimited to scenarios recurrent in SMEs, focusing in particular on pick-and-place and machine-tending applications involving medium-payload cobots. In such applications, the expected performance depends significantly on the design of the entire cell, in addition to the characteristics of the manipulator (Perzylo et al., 2019). In particular, layout, end-effector, and safety

requirements assume central importance, as they shape human-robot interaction and cooperation (Galin & Meshcheryakov, 2019; Boschetti et al., 2023). From this perspective, the cobot is considered as part of a socio-technical system, in which operational, organisational, and safety constraints affect the results that can be achieved (Galin & Meshcheryakov, 2019).

Despite its potential, the introduction of robotics in SMEs encounters technical, economic, and organisational obstacles. In particular, production in SMEs is often less structured, and smaller firms may lack functions and resources dedicated to the design, programming, and maintenance of robotic cells; moreover, traditional programming techniques are poorly suited to frequent changes and customised products in small batches (Perzylo et al., 2019). At the interaction level, close-proximity collaboration makes safety and the design of human-robot interaction central issues, with implications that are not only technical but also social (Galin & Meshcheryakov, 2019). From an economic perspective, investment appraisal requires indicators and assumptions consistent with business decision-making practice: analyses based on ROI and payback show marked sensitivity to production volumes and to the amount of operating time actually saved (Polonara et al., 2024).

To clarify the scope of the analysis and the nature of the decisions addressed, the following adopts an operational distinction between adoption and integration: *adoption* refers to the investment and configuration decision (selection of the alternative and formalisation of the operating assumptions), whereas *integration* refers to the process of implementation and subsequent stabilisation within the work system, understood as the set of operating arrangements, roles, procedures, competences, and safety constraints (including layout and task allocation). This distinction is relevant because it clarifies that the effectiveness of an investment depends not only on the choice of the cobot, but also on the organisational and operational conditions that enable its consistent use over time (Cohen et al., 2019; Perzylo et al., 2019).

Motivation and Research Gap

Recent literature documents the potential benefits of cobots and also analyses, through case studies, the relationship between the adoption of collaborative cells and

competitive priorities such as cost, quality, flexibility, and reliability (Vido et al., 2020). However, three recurring critical issues emerge that motivate this research.

First, the adoption decision requires an integrated assessment: the implementation of cobots raises strategic issues related to the cost-benefit trade-off and socio-organisational effects, in addition to technical aspects (Cohen et al., 2019). Second, translating research findings into operational criteria capable of guiding concrete choices is often complex (that is, where, when, and which cobot to introduce), while taking into account both production constraints and human factors (Cohen et al., 2019; Perzylo et al., 2019). Third, the economic sustainability of integration is sensitive to production conditions: ROI and payback may vary significantly depending on volumes and time saved, making a contextualised assessment necessary, particularly critical for SMEs (Polonara et al., 2024).

In light of these gaps, the thesis proposes an integrated approach that combines a literature review, evidence and application cases reported in the literature, and the development of a decision-making model, with the aim of making the joint assessment of technical, economic, and organisational impacts operational for SMEs.

Research Question and Objectives

This thesis addresses the following research question: how are the technological and competitive transformations of manufacturing driving SMEs towards the adoption of collaborative robots, and how can the technical, economic, and organisational impact of cobots be assessed in a structured way through a literature review, cases and applications reported in the literature, and a dedicated decision-making model?

From this question, the following objectives are derived.

General objective: to develop an analytical framework and a decision-support model to guide manufacturing SMEs in the selection and integration of cobots, assessing their impacts on productivity, economic sustainability, and work organisation.

Specific objectives:

1. To systematise the competitive and technological drivers that motivate the adoption of cobots in SMEs within the framework of manufacturing transformation and Industry 4.0.
2. To frame and classify the types of use and integration logics of cobots in SME contexts, highlighting constraints related to programming, frequent product changeovers, and cell integration requirements.
3. To analyse the organisational impact and the effects on human work, with particular attention to safety and the socio-organisational implications of human-robot interaction.
4. To establish a technical-economic analysis consistent with decision-making metrics typically used by SMEs (TCO, ROI, payback), highlighting the sensitivity of results to production volumes and time saved, also on the basis of evidence available in the literature.
5. To develop a decision-making model that integrates technical, economic, and socio-organisational dimensions, supporting the structured choice of where, when, and which cobot to introduce.

Approach and Methodology

The research adopts a multi-method approach structured into three components. First, a literature review makes it possible to define the drivers, benefits, limitations, and requirements associated with cobot adoption in SMEs, including constraints related to flexibility, programming, and the management of human-robot interaction. Second, the analysis of cases and applications reported in the literature supports the discussion of technical-economic and organisational impacts, providing evidence useful for setting up scenario-based evaluations and comparisons among alternatives. In defining comparable scenarios, the analysis adopts measurable indicators at both workstation and system level (local KPIs and flow KPIs), in order to avoid partial assessments that are not comparable across alternatives. Finally, the thesis develops a decision-making model that combines technical-economic results with strategic and socio-organisational considerations, translating them into operational criteria to support decisions regarding the selection and integration of cobots in SMEs.

Expected Contribution and Target Audience

The expected contribution is twofold. From a scientific perspective, the thesis proposes an integrated interpretation of cobot adoption in SMEs, linking competitive transformations, technical-production configurations, and human-centred and safety-related aspects within collaborative cells. From an applied perspective, the thesis defines an evaluation framework and a decision-making model to support decision-makers in estimating benefits and managing implementation criticalities, with particular attention to the conditions of economic viability and to comparisons among configuration alternatives. The model is developed as an operational artefact (Gate + Scoring), complemented by checklists and SOPs; the thesis proposes a conceptual verification of the model and formalises a replicable empirical validation plan for future developments. The main target audience consists of manufacturing SMEs, production and industrial engineering managers, as well as professionals involved in the design and management of flexible automation systems.

Structure of the Thesis

Chapter 1 frames the transition from traditional industrial robotics to collaborative robotics, as well as the competitive and technological drivers underpinning interest in digital transformation and Industry 4.0, with particular attention to the implications for SMEs. Chapter 2 analyses the types of cobot use in SMEs and proposes a classification of applications, with a focus on pick-and-place and machine-tending, highlighting the technical and integration requirements of the cell (layout, EOAT, interfaces, and safety), as well as production KPIs (local and flow-related), in addition to the main implementation challenges. Chapter 3 examines the organisational impact and the implications for human work, discussing safety, task allocation, and human-centred principles in the design of the collaborative cell. Chapter 4 develops the technical-economic analysis of cobot integration in SMEs, referring to key metrics and critical factors (e.g. ROI, payback, and dependence on volumes and time saved) and discussing evidence and applications available in the literature in order to establish scenario-based comparisons. On the basis of these outputs, Chapter 5 formalises an operational decision-making model (Gate + Scoring), integrated with checklists and SOPs, discusses its assumptions and

limitations, provides a conceptual verification, and formalises a replicable empirical validation plan (simulation and/or case study) as a future development.

In light of this structure, the following chapter introduces the relevant technological and industrial framework, outlining the drivers that motivate the adoption of cobots in manufacturing SMEs.

Chapter 1

FROM TRADITIONAL INDUSTRIAL ROBOTICS TO COBOTS: EVOLUTION, PRINCIPLES, AND ADOPTION DRIVERS

1.1 Evolution of Automation: From Traditional Robots to Cobots

This section frames the transition from traditional industrial robotics to collaborative robotics by comparing the main technological, operational, and application-related differences between conventional robots and collaborative robots, and by synthesising the factors that are fostering their adoption in manufacturing firms. In particular, the aim is to highlight that cobots do not merely constitute a new generation of manipulators, but rather represent the expression of a “hybrid” automation paradigm: an arrangement in which the controlled sharing of the workspace, the reduction of setup and reprogramming times, and a different organisation of tasks between operator and robot make automation feasible even in contexts characterised by high variability and small batch sizes, typical of many SMEs (Giberti et al., 2022; Kopp et al., 2020; Keshvarparast et al., 2024).

Consistently with the decision-making model developed in Chapter 5, the present study distinguishes between *adoption*, understood as the investment and configuration decision (selection of the alternative and formalisation of the operating assumptions), and *integration*, understood as the process of implementation and subsequent stabilisation within the work system (layout, task allocation, safety/work system, competences, and operating routines). This distinction is relevant because it clarifies that the drivers discussed in this chapter will subsequently be operationalised as assumptions, constraints, and evaluation criteria within the framework.

1.1.1 Industrial Robots vs Cobots

Traditional industrial robotics became established in the context of mass production, oriented towards maximising productivity and repeatability over high

volumes (Keshvarparast et al., 2024). In this scenario, robots are designed to ensure high speeds, large payloads, and precision, but they generally operate in cells segregated by physical barriers and dedicated protection systems, with limited interaction with the operator during the production cycle (Keshvarparast et al., 2024). This results in rigid layouts, significant space requirements, and a strong specialisation of cells for specific products or processes; moreover, programming, entrusted to expert technical personnel, requires considerable time and competences (Giberti et al., 2022). Consequently, investments in traditional robotics are more justifiable in the presence of stable and repetitive volumes, whereas they are less effective when production plans require frequent product changeovers or small batch sizes (Giberti et al., 2022). In the high-variability contexts typical of many SMEs, plant rigidity and integration costs often make the adoption of traditional robotic cells economically unattractive (Kopp et al., 2020).

Collaborative robots emerged as a response to these limitations. Collaborative robotics is described as a general category encompassing proximity and interaction between machines and people for the execution of tasks within a shared space; within this framework, protection systems and standardisation constitute central elements for making industrial applications feasible (Vicentini, 2020). Consistently, cobots are designed to operate in close proximity to operators and, under certain conditions, to share the same workspace thanks to a lighter mechanical design, force and power limiting functions, and control and sensing systems that enable the safe management of interaction (Vicentini, 2020; Santoni & Lucato, 2021).

It is, however, essential to clarify that “collaborativeness” is not an absolute property of the machine alone, but depends on the specific application and on the safety arrangement defined by the risk assessment. In other words, cobots enable collaborative or shared workstations that are less segregated than traditional cells, but any need for fencing, scanners, or additional safety devices depends on the task, the end-effector, the context, and the measures adopted. Collaboration may be based on different strategies (for example, force/power limiting and speed and separation monitoring), in compliance with the safety requirements defined by international norms and standards (Vicentini, 2020).

The differences also concern programming paradigms. The literature highlights that, compared with more traditional approaches, programming is evolving towards more accessible methods (for example, learning by demonstration and physical interaction), with the aim of reducing the effort and competences required (Giberti et al., 2022). In this direction, cobots often adopt user-friendly graphical interfaces and manual arm-guiding modes (*teach-in*), which allow trajectories and tasks to be taught by demonstration, thereby reducing setup times and the need for advanced programming competences (Giberti et al., 2022; Santoni & Lucato, 2021).

These differences give rise to a different logic of use. Traditional industrial robots are mainly intended to replace human labour in repetitive and standardised operations (Keshvarparast et al., 2024). Cobots, by contrast, are designed to cooperate with the operator, combining human capabilities (dexterity, adaptation, decision-making) with the strengths of robots (strength, endurance, repeatability), with additional benefits in ergonomic terms in repetitive or strenuous activities (Faccio et al., 2023). In summary, traditional robotics prioritises performance and full automation in stable contexts, whereas collaborative robotics emphasises safe co-presence, faster setup, and reconfigurability, thereby supporting hybrid automation models that are particularly relevant in the variable production environments of SMEs (Kopp et al., 2020; Keshvarparast et al., 2024).

1.1.2 *Drivers of the Transition*

The differences outlined above explain the growing interest of manufacturing firms, particularly SMEs, in cobots. The drivers of this transition primarily concern technical and production-related dimensions: contemporary production systems are characterised by increasing customisation, demand instability, and smaller batch sizes, with a consequent increase in variety and a growing need for high flexibility (Simões et al., 2020; Keshvarparast et al., 2024). Under these conditions, traditional automation shows limited penetration, since the design and integration costs of dedicated cells are sustainable mainly for high volumes and become economically unattractive when frequent product changeovers are required (Giberti et al., 2022). As a result, many firms continue to rely on manual labour or on forms of “light”

automation, even where there is room for efficiency improvements (Kopp et al., 2020).

Cobots make it possible to automate repetitive or demanding operations while maintaining a high degree of flexibility: the possibility of repositioning the robot, rapidly reconfiguring the task, and integrating it into collaborative or shared workstations makes it possible to adapt the workstation to changes in demand without redesigning the entire layout (Giberti et al., 2022; Kopp et al., 2020). Collaborative robotics thus makes automation feasible even in small- and medium-batch production, where traditional solutions often prove too rigid or too costly (Kopp et al., 2020).

From an economic perspective, several analyses emphasise that cobots can contribute to improving productivity and quality, simplifying programming and reducing investment payback times, while also offering portability and potential cost advantages in many applications (Bloss, 2016). Consistently, adoption may be encouraged when the reduction in fixed deployment costs and in setup and reconfiguration times lowers the volume threshold beyond which automation becomes economically viable (Kopp et al., 2020; Giberti et al., 2022). At the same time, in human-robot collaboration (HRC) configurations, actual performance depends on the real operating configuration and on safety constraints: this introduces a safety-performance trade-off that may affect speed, cycle times, and capacity.

A further set of drivers concerns organisational and human dimensions. Within the Industry 4.0 framework, collaborative robotics is often interpreted through a human-centred lens, with effects on ergonomics, job design, and the reallocation of activities (Faccio et al., 2023). The introduction of cobots makes it possible to reduce the physical workload associated with repetitive or strenuous tasks and to redirect operators towards supervisory activities, quality control, and problem solving, thereby contributing to improved working conditions and the enhancement of competences (Faccio et al., 2023). At the same time, the literature on adoption highlights that barriers related to competences and acceptance may limit their full exploitation, especially in smaller firms; these aspects will be discussed in the following paragraphs (Simões et al., 2020; Keshvarparast et al., 2024).

Finally, the transition is supported by a regulatory framework that has progressively defined the safety requirements of collaborative systems. Norms and standards relating to industrial robots and collaborative applications provide guidance for managing the risks associated with workspace sharing and for designing shared workstations, thereby reducing uncertainty for firms and system integrators (Vicentini, 2020).

In summary, the transition from traditional industrial robots to cobots is driven by the alignment between new production needs (flexibility, customisation, batch-size reduction, and rapid reconfiguration) and new technological possibilities (safe co-presence, sensing systems, and more accessible programming), together with economic, organisational, and regulatory drivers (Giberti et al., 2022; Kopp et al., 2020; Faccio et al., 2023; Vicentini, 2020; Bloss, 2016). In the following paragraphs, Section 1.2 examines the definitions and operating principles of collaborative robotics in greater depth, while Section 1.3 analyses the specific features of adoption in manufacturing SMEs, thereby completing the framework necessary to answer the research question.

1.2 Cobots: Definitions, Characteristics, and Operating Principles

Building on the transition from traditional automation to collaborative robotics, this section outlines:

- i. the main definitions of collaborative robot found in the scientific literature and industrial standards;
- ii. the technical and operational enablers that make their use in manufacturing possible: functional safety, sensing and environmental perception, simplified programming, and the principles of human-robot collaboration (HRC) (Simões et al., 2020; Keshvarparast et al., 2024).

From this perspective, collaborative robotics is frequently associated with expected benefits in terms of ease of programming and integration and, in some contexts, also productivity; however, such outcomes depend on the specific operating configuration and on HRC/safety constraints, which affect the operating conditions (Bloss, 2016). The analysis is organised into five sections: definitions and the regulatory framework, safety and collaborative modes, sensing and perception,

programming and interfaces, and the operating principles of HRC, with the aim of clarifying how these elements contribute to making the integration of cobots into production applications feasible.

1.2.1 *Definitions and Regulatory Framework*

The literature defines collaborative robots as robotic systems capable of manipulating objects and performing industrial tasks while sharing the workspace with the human operator and enabling, in different forms, direct interaction, thereby reducing the need for the complete segregation typical of traditional robotic cells (Colgate et al., 1996; Bauer et al., 2016; Simões et al., 2020). Vicentini (2020) uses the term *collaborative robotics* to describe situations in which humans and robots operate in proximity according to different temporal configurations (continuous, alternating, synchronous), highlighting that the distinguishing element lies in the controlled sharing of space and time rather than in the nature of the task itself (Vicentini, 2020).

International standards formalise these concepts. ISO/TS 15066:2016 defines *collaborative operation* and *collaborative workspace* as applications in which humans and robots can coexist within the same working volume and, under certain conditions, come into controlled physical contact (ISO/TS 15066:2016). In combination with ISO 10218-1:2025 (safety requirements for industrial robots as robotic components intended for integration into systems) and ISO 10218-2:2025 (requirements for systems and integration), this framework makes it possible to distinguish collaborative applications from segregated ones (ISO 10218-1:2025; ISO 10218-2:2025; ISO/TS 15066:2016). Within the standards, therefore, “collaborativeness” is defined primarily as a property of the operation and of the safety arrangement of the specific application. Consequently, the label *cobot* depends on the set of operating conditions and on the measures adopted to ensure safe co-presence, which in turn shape the mechatronic architecture and control logics (Vicentini, 2020; Bi et al., 2021). In practice, many implementations classified as collaborative robotics remain at the level of simple coexistence, highlighting a gap between the regulatory framework and actual use (Simões et al., 2020; Keshvarparast et al., 2024).

In summary, the literature and the standards converge in describing cobots as systems and applications designed for safe co-presence with the operator; empirical evidence, however, indicates that fully developed collaborative configurations are still relatively uncommon (Simões et al., 2020; Keshvarparast et al., 2024).

1.2.2 *Safety and Collaborative Modes*

Safety constitutes the distinctive technical element in comparison with conventional industrial robotics. In traditional robots, operator protection is ensured mainly through physical segregation (fenced cells, guards, photoelectric barriers), whereas in collaborative applications it is ensured through an integrated design of mechanics, sensors, and control, framed by functional safety requirements and risk assessment (Vicentini, 2020; Faccio et al., 2023). In this sense, safety and standardisation represent central dimensions in industrial collaborative robotics (Vicentini, 2020).

ISO 10218-1:2025, ISO 10218-2:2025, and ISO/TS 15066:2016 identify four main collaborative modes:

- i. *safety-rated monitored stop* (SRMS);
- ii. *hand guiding*;
- iii. *speed and separation monitoring* (SSM);
- iv. *power and force limiting* (PFL) (ISO 10218-1:2025; ISO 10218-2:2025; ISO/TS 15066:2016).

These modes translate into specific design solutions: lightweight arms with rounded geometries and no sharp edges, surfaces free of pinch points, torque-limited actuators, and control systems capable of slowing down or stopping the robot according to the operator's approach and the operating conditions defined by the risk assessment (Faccio et al., 2023). Bi et al. (2021) emphasise that this requires a higher degree of control autonomy, as the system must react in real time to changes in the human environment.

It follows that safety does not represent merely an external constraint, but rather a property designed “into the system”, which makes workspace sharing feasible and can facilitate integration into existing manufacturing lines, reducing, in many cases,

the need for complete segregation in the application set-up (Vicentini, 2020; Faccio et al., 2023).

1.2.3 *Sensing and Perception*

A second key characteristic of cobots concerns sensing and the ability to perceive the environment. Compared with many conventional industrial robotics applications, in which environmental and operator perception is frequently entrusted to external components and to application-specific design, cobots are more often conceived to integrate (or natively provide) sensors and control functions that are useful for collaboration and the safe management of proximity. Within this framework, force/torque sensors, vision systems, proximity sensors, and devices for monitoring the operator's position support both task execution (for example, in the assembly of variable components) and the implementation of safety modes such as SSM and PFL, in which the system must continuously estimate distances and forces in order to keep risk within acceptable thresholds (Krüger et al., 2009; Fryman & Matthias, 2012; Bi et al., 2021; Faccio et al., 2023). These variables (distances, speeds, separations, and contact forces), which in the model are made explicit as operating assumptions (e.g. zones/speeds/separations), influence the expected cycle times and throughput and, consequently, must be explicitly incorporated into the analysis of alternatives.

The literature highlights that these perceptual capabilities make it possible to move beyond rigidly pre-programmed control, enabling the system to adapt to the operating context and to modify trajectories and speeds in response to objects, obstacles, or human movements (Simões et al., 2020; Keshvarparast et al., 2024). Advanced sensing thus becomes the channel through which the cobot establishes a situated interaction with the environment and with the operator, making possible a form of collaboration that may go beyond mere co-presence and include dynamic coordination (Bi et al., 2021; Faccio et al., 2023).

Consequently, sensing does not represent an accessory element, but rather a technical prerequisite for operating in less structured production environments characterised by variability in parts and paths, a frequent condition in high-variety manufacturing applications (Simões et al., 2020; Keshvarparast et al., 2024).

1.2.4 *Simplified Programming and Interfaces*

A third pillar of collaborative robotics concerns simplified programming paradigms. The literature highlights that one of the main obstacles to the adoption of traditional robotics is the need for expert programmers and long commissioning and setup times, factors that reduce the economic viability of automation when frequent product or process changes are required (El Zaatari et al., 2019; Simões et al., 2020; Giberti et al., 2022). Within this framework, attention to ease of programming and to the reduction of investment payback time recurs in industrial discussions on collaborative robotics (Bloss, 2016). Cobots address this critical issue by introducing human-machine interfaces oriented towards shop-floor operators, including programming by demonstration (*walk-through programming*), graphical touch panels, and, in some cases, gesture- or voice-based input (Ferraguti et al., 2017; Santoni & Lucato, 2021; Faccio et al., 2023).

Giberti et al. (2022) propose a *skill-based programming* approach that decomposes the task into elementary “skills” configurable through guided procedures; the results indicate a significant reduction in setup times and greater economic sustainability in the use of cobots even in small- and medium-batch production. In an applied study, Santoni and Lucato (2021) find that simplified interfaces are perceived by operators as one of the main advantages of cobots, together with the improvement of ergonomic conditions. These findings are consistent with Simões et al. (2020), who identify the reduction of programming complexity as a central driver of adoption intentions.

In summary, user-oriented programmability lowers the threshold of required competences, facilitates the rapid reconfiguration of workstations, and makes collaborative automation more compatible with manufacturing contexts in which setup and reconfiguration times have a decisive impact on the economic viability of the investment (Giberti et al., 2022; Simões et al., 2020; Keshvarparast et al., 2024).

1.2.5 *Operating Principles of Human-Robot Collaboration*

The characteristics described so far translate into specific operating principles of collaboration. The literature distinguishes between *coexistence* scenarios, in which humans and robots share the same area but work on different objects or stages, and

close collaboration scenarios, in which they operate on the same component in a coordinated manner (Bauer et al., 2016; Simões et al., 2020; Keshvarparast et al., 2024). Empirical evidence indicates that many real applications remain anchored to coexistence: the cobot performs a task autonomously, while proximity to the operator allows more compact workflows and better balancing of operations along the line. This points to a gap between the collaborative potential outlined in the standards and the level of integration actually achieved (Simões et al., 2020; Faccio et al., 2023; Keshvarparast et al., 2024).

Beyond the degree of integration, the logic of HRC lies in combining human and robot capabilities in a complementary way. The cobot contributes repeatability, precision, and execution consistency, supporting repetitive or physically demanding tasks and reducing the operator's exposure to biomechanical loads; the operator contributes cognitive flexibility, problem-solving ability, and fine dexterity (Krüger et al., 2009; Matheson et al., 2019; Faccio et al., 2023). Task allocation must therefore be designed systematically, taking into account cycle times, safety constraints, and ergonomic risks: Gualtieri et al. (2020) and Faccio et al. (2023) propose models and guidelines aimed at maximising overall productivity and reducing the operator's physical workload.

The human-centred dimension represents a guiding principle of HRC. Systematic reviews show that the effectiveness of cobots is assessed not only in terms of productive output, but also in relation to ergonomics, the reduction of biomechanical risks, and workers' perception of safety and comfort (Pinheiro et al., 2021; Gualtieri et al., 2020). At the same time, the presence of the robot in the operator's workspace may generate stress or uncertainty if layout, signals, and interaction modes are not designed with care (Chemweno et al., 2020; Faccio et al., 2023). It follows that the effective implementation of HRC requires an integrated approach that combines technical criteria and human factors, preventing design or organisational choices from reducing the potential of collaborative automation (Vicentini, 2020).

In conclusion, Section 1.2 has shown that cobots, understood as systems and applications oriented towards the controlled sharing of space, are based on functional safety, advanced sensing, simplified programming, and the operating principles of human-robot collaboration, which make it possible to employ them in close contact

with operators on manufacturing lines (Vicentini, 2020; Simões et al., 2020; Giberti et al., 2022; Keshvarparast et al., 2024). Empirical evidence nonetheless shows that the configurations actually implemented are often limited to coexistence and conditioned, among other factors, by competence constraints and by the quality of the design of interaction and human factors (Simões et al., 2020; Chemweno et al., 2020; Faccio et al., 2023). These four dimensions (safety, sensing, programmability, and HRC principles) also constitute the technical core through which cobots can respond to the typical constraints of SMEs (variability, small batch sizes, and rapid reconfiguration), a theme developed in Section 1.3.

1.3 Collaborative Robots in SMEs and Differences Compared with Large Enterprises

This section analyses how the typical requirements of manufacturing SMEs (high flexibility, small-batch production, and rapid changeover) influence the adoption of collaborative robots as compared with large enterprises. It also examines which cobot characteristics are most relevant in meeting these requirements. Building on the distinction introduced in Section 1.1 between *adoption* (the investment and configuration decision) and *integration* (implementation and stabilisation within the work system), the following considerations clarify the factors that guide SMEs' choices and the conditions that influence their outcomes.

In general terms, collaborative robotics is commonly described as a set of solutions that enable human-robot proximity in shared spaces by leveraging safety, more intuitive interaction modes, and characteristics oriented towards greater ease of use (e.g. simplicity of programming and portability), with expected effects on productivity and costs across a wide range of industrial applications (Vicentini, 2020; Bloss, 2016).

In light of this, a distinction can be drawn between:

- i. characteristics that are decisive for managing variability and rapid changeovers (rapid programmability, reconfigurability, and reuse across multiple workstations/variants);

- ii. enabling characteristics for adoption in SMEs (gradual integration, portability, and application-level safety requirements compatible with existing layouts);
- iii. organisational conditions that affect the success of projects (available competences, time for experimentation, and operator involvement).

1.3.1 *Flexibility Requirements, Small Batch Sizes, and Rapid Changeovers in SMEs*

Automation decisions are made in production contexts that differ between large enterprises and SMEs. Large manufacturing firms, especially in high-volume sectors with standardised processes, are better able to exploit traditional industrial robots on a continuous basis, as these are oriented towards speed, repeatability, and the intensive use of dedicated cells. In such scenarios, rigid automation is justified by long time horizons and relatively stable demand, which make it possible to amortise integration and programming costs over large production runs.

SMEs, by contrast, more often operate under conditions of volatile demand, high variety, and short life cycles, typical of high-mix/low-volume configurations: small or medium batch sizes, frequent product changeovers, and increasing customisation. Under these conditions, the engineering and reconfiguration costs of dedicated cells weigh on limited volumes, and the downtime associated with changeovers becomes critical. In addition, the lower availability of internal resources for programming and maintenance reduces the sustainability of solutions that require continuous specialist competences. As a result, for many SMEs, rigid automation is difficult to justify, and the use of manual or semi-automatic systems often represents a constrained choice rather than a strategic one.

Within this framework, cobots are interpreted as a technology capable of reconciling automation and flexibility. Several studies suggest that cobots make automation economically feasible even at lower volumes than traditional robotic cells. Consequently, the point at which rigid automation becomes the most efficient choice tends to occur at higher production volumes, whereas for small- or medium-scale production cobots are more competitive thanks to lower reconfiguration times and costs (Kopp et al., 2020; Giberti et al., 2022). The possibility of moving the robot between workstations, reusing equipment and programs across multiple

variants, and rapidly reconfiguring the system as the product changes makes it possible to contain changeover times and increase the utilisation rate of capital equipment in contexts of fragmented demand (Giberti et al., 2022).

A crucial role is played by simplified programmability and interfaces oriented towards the shop-floor operator. Approaches that decompose the task into reusable and parametric “skills”, configurable through guided procedures or by demonstration, significantly reduce setup times compared with traditional robot programming languages, thereby making the use of cobots more feasible in contexts characterised by frequent product variations (Giberti et al., 2022; Simões et al., 2020). It follows that, even in the absence of a dedicated programming department, the introduction of collaborative robots can be managed by process technicians or appropriately trained operators, without requiring advanced robot programming competences.

In summary, the flexibility requirements, small batch sizes, and rapid changeovers typical of SMEs make certain decisive characteristics of cobots central (reconfigurability, reuse across multiple workstations/variants, and intuitive programmability), distinguishing them from conventional rigid automation and helping to explain their theoretical attractiveness for smaller firms.

1.3.2 Drivers of the Transition towards Cobots in SMEs

The technical-production requirements described above translate into motivations that drive SMEs towards collaborative robotics and, at the same time, help to explain its still limited diffusion.

From a technical perspective, cobots make it possible to introduce automation into workstations that were previously exclusively manual thanks to safety technologies and standards, the possibility of operating in proximity to the operator in specific operating scenarios, and greater ease of use, including simplified programming and portability, thereby reducing the need for dedicated layouts (Vicentini, 2020; Bloss, 2016). This facilitates gradual integration and, in some cases, limits the need to redesign the entire plant. In addition, the combination of the robot’s repeatability and the operator’s adaptability is particularly suited to assembly, handling, and machine-feeding operations, which are common in high-variety SMEs (Giberti et al., 2022;

Faccio et al., 2023). Safety and human-robot collaboration aspects (Section 1.2) are particularly relevant here because of their practical implications: the possibility of introducing the cobot into existing departments while reducing the spatial barriers and segregation constraints typical of rigid cells. From this perspective, technical feasibility must also be understood as verifiable compatibility with layout/space requirements, process interfaces, tooling (EOAT), and integration constraints with existing machines and systems.

From an economic perspective, cobots are regarded as a means of increasing productivity and quality while maintaining the ability to manage high variability. Technical-economic analyses indicate that the reduction of changeover times, the reusability of programs, and the use of the same cobot across multiple stations can improve the profitability of the investment compared with traditional solutions when production volumes do not allow specialised cells to be fully utilised (Giberti et al., 2022; Kopp et al., 2020). However, the literature indicates that independent quantitative evidence on efficiency gains and economic returns remains limited and that many decisions are based on qualitative assessments or manufacturers' estimates (Kopp et al., 2020; Keshvarparast et al., 2024). This uncertainty tends to weigh more heavily on SMEs, where the ability to absorb investment risk is more limited: as a result, a cautious approach often emerges, based on pilot projects and progressive implementations rather than on large-scale automation programmes. Although sometimes lower than those associated with traditional cells, the initial investments and, above all, the overall integration costs (end-effector, possible sensing systems, application-level safety, plant downtime, and staff time) may still remain significant for firms with limited resources.

Organisational and human motivations are equally relevant. Studies on adoption intentions show that organisational receptiveness, the availability of time and resources for experimentation, basic technical competences, and worker involvement decisively influence SMEs' choices (Simões et al., 2020; Keshvarparast et al., 2024). Collaborative robotics is often framed within a human-centred model, in which the operator retains responsibility for control, problem solving, and the management of variants, while the cobot takes on repetitive or strenuous activities (Faccio et al., 2023; Santoni & Lucato, 2021). At the same time, operational proximity requires

careful management of socio-technical factors (e.g. ergonomics, trust, and the perception of safety), which may affect project outcomes (Chemweno et al., 2020; Faccio et al., 2023). For SMEs, characterised by lean organisational structures and limited resources for change management, these criticalities may be amplified: lack of time for training, the absence of figures specifically dedicated to process optimisation, and constraints related to space and infrastructure may slow down or prevent the transition even where the technical-economic case appears favourable (Simões et al., 2020; Kopp et al., 2020).

Overall, the transition towards cobots in SMEs arises from the interweaving of technical, economic, and organisational drivers: automating without losing flexibility, limiting exposure to risk, and preserving-while enhancing-the contribution of people. Cobots emerge as a promising response, but the gap between potential and actual adoption suggests the need for evaluation tools and guidelines specifically oriented towards smaller firms (Kopp et al., 2020; Simões et al., 2020; Keshvarparast et al., 2024).

Since, in HRC mode, performance and safety are not independent, the assessment must be task-based and scenario-based, making explicit for each alternative the HRC operating assumptions on which performance, safety constraints, and economic outcomes jointly depend. These assumptions include, for example, zone configuration, speed parameters, and distances/separations.

Consistently with the distinction proposed between decisive and enabling characteristics, the following synthesis links production requirements and technological and organisational levers. The evidence discussed makes it possible to trace the main requirements of SMEs back to a coherent set of cobot characteristics:

- Rapid changeovers and frequent product changes: simplified programmability, reuse of skills/programs, guided or demonstration-based procedures, and rapid reconfiguration;
- Small-batch production and high variety: reuse of the cobot across multiple variants and workstations, tooling modularity, and rapid restoration of operations;
- Flexibility and layout constraints: portability, gradual integration, and application-level safety requirements compatible with existing departments;

- Limited resources and competences: operator-oriented interfaces, reduced need for specialist programming, and greater ease of operational management, while still acknowledging the weight of socio-technical factors and change management.

On the basis of these relationships between requirements and technological and organisational levers, the following chapter examines in greater depth the productive and organisational impacts of collaborative robotics and introduces the elements necessary for a more systematic assessment, with particular attention to implementation conditions in SMEs.

Chapter 2

MEDIUM-PAYLOAD COBOTS IN SMES: CLASSIFICATION OF APPLICATIONS, PRODUCTIVITY KPIs, AND INTEGRATION CHALLENGES

2.1 Classification of Cobot Applications in SMEs and Focus on Medium Payload

In the context of manufacturing SMEs, a classification of collaborative robot applications is useful for relating:

- i. the perceived industrial priority;
- ii. the technical requirements for cell integration (EOAT, sensing, safety logics, layout configuration, and interfaces);
- iii. the level of dependence on perceptual capabilities and digital infrastructures.

From this perspective, such a classification makes it possible to distinguish applications that are more readily adoptable from those requiring greater technological and organizational maturity, and to link integration choices to specific technical and operational requirements.

The aim of this section is to reconstruct, on the basis of the literature, a reasoned classification of the main cobot applications in SMEs, highlighting their industrial priority and levels of technical-integration complexity. The analysis focuses on pick-and-place and machine-tending (load-unload) applications with medium payloads (5-12 kg), since this range defines a recurring set of tasks typical of SMEs (handling of components and semi-finished products, machine tending) in which the expected performance depends primarily on process stability and the design of the entire cell. In such applications, layout, EOAT, and basic industrial sensing (I/O, presence/position sensors, interlocks) generally prove more decisive than advanced perceptual capabilities based on vision systems or complex data processing. By contrast, domains such as assembly and automated inspection often present more

selective requirements, respectively in terms of dexterity/task variability and the maturity of perception and data-management systems.

From this standpoint, Fast-Berglund et al., on the basis of seven workshops involving 40 SMEs and 6 OEMs, propose a map of recurring application areas and highlight differing priorities between SMEs and OEMs. SMEs place pick-and-place and machine-tending among the highest-priority areas, whereas OEMs assign greater importance to pre-assembly and final assembly activities. This divergence appears consistent with the production profile of the sample, largely composed of subcontractors with a strong presence of machining operations, for whom machine tending and repetitive handling represent core functions (Fast-Berglund et al., 2019).

It follows that a classification jointly considering industrial priority, the technical-integration complexity of the cell, and the degree of dependence on layout, sensing, and data infrastructures makes it possible to position pick-and-place and machine-tending more precisely in relation to domains that are more demanding from a perceptual or digital standpoint. From this perspective, the focus on medium payload is not merely a technical constraint: it defines a set of tasks in which performance depends on the combination of manipulator capabilities and the quality of cell design, rather than on the arm considered in isolation. The classification therefore provides the conceptual foundation for the analysis of productivity KPIs (Section 2.2) and for the discussion of barriers to adoption (Section 2.3); the recurring requirements that emerge will be taken up again in the following chapters in order to structure the comparison among alternative integration solutions.

2.1.1 *Pick-and-place*

Pick-and-place is one of the most established applications of collaborative robotics and, in the context of SMEs, it is frequently regarded as one of the most accessible uses in terms of implementation and expected return (Fast-Berglund et al., 2019). Operationally, the repetitive nature of the task and the relative stability of the context facilitate cycle definition and the preliminary estimation of the expected benefits in terms of productivity and ergonomics. The literature also suggests human-centred criteria as a cross-cutting design dimension even in simpler handling

applications, with implications for safety, acceptance, and the overall performance of the cell (Faccio et al., 2023; Boschetti et al., 2022).

The effectiveness of pick-and-place does not depend on the manipulator alone, but on the design of the entire cell. Ronzoni et al., in their analysis of an end-of-line application in the food service sector, show that the integration of a UR10 cobot (10 kg payload) with a Venturi-effect gripper requires a redesign of the layout and a sensor/actuator architecture aimed at ensuring the stability of pick positions, verifying the presence of parts, and managing buffers. The authors also highlight that material-orienting devices and sensors for measuring distances and heights increase grasp robustness, and they describe a safety protocol based on error categories that activate either a full stop or a reduced mode depending on field signals (Ronzoni et al., 2021).

Overall, pick-and-place with medium payloads appears to be highly transferable to SMEs, provided that layout, EOAT, and sensing are designed in an integrated manner. In particular, the realistic definition of the expected KPIs requires consideration not only of the payload (including EOAT), but also of reach and repeatability in relation to the process quality requirements; together with layout constraints and grasp robustness, these elements determine the feasibility and stability of the cycle and also provide a useful basis for the analysis of machine tending.

2.1.2 Machine tending

Machine tending is particularly relevant for SMEs operating machining processes. The literature indicates that such firms assign high priority to this application, also in relation to their subcontracting role and the widespread presence of CNC machining, drilling, and milling operations. In many cases, machine tending enables the introduction of collaborative applications in configurations of coexistence or synchronized interaction, with levels of interaction generally lower than those found in tightly collaborative assembly, thereby reducing some of the initial barriers related to internal acceptance and interaction management (Fast-Berglund et al., 2019; Gualtieri et al., 2020; Gualtieri et al., 2021).

From a technical perspective, machine tending requires grasp reliability, trajectory repeatability, and compatibility with the interfaces of the serviced machine; the choice of payload is therefore directly related to the mass of the workpieces and the characteristics of the EOAT. Application complexity is often determined by the robustness of machine-cobot integration and the operational continuity of the cell: key aspects include the integration of I/O signals, cycle handshake logic, the management of access constraints and operating sequences (for example, opening/closing and constrained positioning), and consistency with interlocks and safety requirements. Moreover, in collaborative configurations, the constraints of human-robot collaboration (zones, speeds, separation distances) must be explicitly defined, since these constraints affect the operational assumptions and the expected KPIs (for example, cycle times and actual throughput).

Compared with pick-and-place, machine tending depends more heavily on the machine-cobot interface and on the coordination of inbound and outbound flows. Nevertheless, it presents a level of complexity that is often compatible with gradual adoption strategies in SMEs, especially when the payload falls within a medium range consistent with the semi-finished products typically handled by subcontractors. In this sense, machine tending with 5-12 kg cobots emerges as one of the main candidates for initial collaborative pilot implementations in contexts characterized by a significant presence of machine tools.

2.1.3 *Light Assembly*

For comparative purposes, light assembly exhibits, on average, a higher level of complexity than pick-and-place and machine tending, since the critical factors are often determined more by dexterity, precision, and process variability (feeding, orientation, insertions) than by payload itself. The literature reports that, although assembly falls among the areas of cobot application, it is often perceived by SMEs as a subsequent stage following handling and machine-tending tasks (Fast-Berglund et al., 2019).

Technical studies (for example, Gualtieri et al.) show that feeding and assembly-related criticalities (magnetic, flexible, or fragile components, lack of clear geometric references, need for high dexterity or the use of both hands) may reduce suitability

for standard robotization and increase the risk of unsuccessful implementation in contexts with limited experience in collaborative automation (Gualtieri et al., 2020; Gualtieri et al., 2021). These findings are referred to exclusively in order to position the domain with respect to the focus of this chapter, without making it an object of the KPI analysis in Section 2.2.

2.1.4 *Quality Control*

Quality control represents a domain in which complexity depends less on the manipulator payload and more on the maturity of perception systems and data-management capabilities. The literature associates inspection applications with uses based on computer vision to assess the condition of parts or products (Fast-Berglund et al., 2019). Contributions such as Židek et al. highlight that digitalized inspection requires integration among vision systems, traceability, and data infrastructures, with critical issues related to calibration and interpretive robustness (Židek et al., 2020). Here too, the reference serves to delimit the scope: such applications are considered more demanding from an IT/OT perspective than the target applications of pick-and-place and machine tending.

2.1.5 *Section Summary*

The literature makes it possible to outline a classification of cobot applications in manufacturing SMEs that integrates industrial priority, the technical-integration requirements of the cell, and the degree of dependence on perception and digital infrastructures. Within this framework, pick-and-place and machine tending with medium payloads emerge as areas that are frequently prioritized in SMEs, in which performance depends decisively on layout, EOAT, sensing, and cell safety (Fast-Berglund et al., 2019; Ronzoni et al., 2021). By comparison, light assembly and quality control present more selective requirements, respectively in terms of dexterity/variability and digital prerequisites (Gualtieri et al., 2020; Gualtieri et al., 2021; Židek et al., 2020). On the basis of this delimitation, Section 2.2 synthesizes the available evidence on the impacts of the two target applications on KPIs, distinguishing between direct measures and proxy-based results.

2.2 Measurable Benefits of Pick-and-Place and Machine-Tending Applications

In evaluating the use of cobots in manufacturing SMEs, the benefits most relevant to investment decisions are those that can be translated into operational performance indicators. From this perspective, pick-and-place and machine-tending applications involving medium-payload cobots fall among the areas for which the impacts on productivity, process stability, and working conditions are, in the literature, relatively better documented than for more complex collaborative applications (Gualtieri et al., 2020; Faccio et al., 2022). Studies focused on SMEs also show that such firms often associate the introduction of cobots with joint objectives of ergonomic improvement and greater production-system efficiency, in continuity with lean and human-centred design approaches (Fast-Berglund and Romero, 2019; Colim et al., 2021).

Consistent with the objective of this chapter, this section analyses the benefits associated with pick-and-place and machine tending with respect to the main KPIs: cycle time, OEE or its components, scrap rate/quality, process variability, and ergonomics. Where case studies provide “before/after” comparisons, the traditional manual scenario is taken as the baseline; in the absence of a measured baseline, the results discussed are interpreted as transferable or indirect evidence, useful for identifying the expected direction of impact on KPIs, but not equivalent to a complete quantification.

From a methodological standpoint, studies on collaborative cells propose sets of KPIs consistent with typical production indicators (for example, cycle time and throughput, resource waiting times, cobot utilization rate, and measures of overall efficiency), sometimes referring to the recommendations of ISO 22400 (Aliev et al., 2019; Ronzoni et al., 2021). However, in many contributions, OEE and scrap reduction are not calculated in aggregated form: more frequently, partial indicators are measured (waiting times, completed cycles, resource utilization), which can be interpreted as proxies for OEE components and are useful for understanding flow stability (Aliev et al., 2019). Consequently, this section distinguishes between direct quantitative results and proxy-based results, explicitly indicating where the literature reports measurement gaps for consolidated KPIs (in particular, overall OEE and scrap rate).

In line with the decision-making model presented in Chapter 5, the literature and the comparison among scenarios prioritize a set of “core” KPIs that are always comparable across alternatives: throughput/equivalent cycle time, resource utilization, bottlenecks, and labour requirements. Where the scope includes line/cell interdependencies that cannot be reduced to the single task, the analysis incorporates system-level KPIs such as average WIP, waiting times, lead time, and output variability. This distinction makes it possible to relate the indicators reported in the literature (often partial or proxy-based) to the components required for a scenario-based evaluation and for their subsequent economic translation.

Since the literature often reports partial measures rather than aggregated OEE, Table 2.1 summarizes the correspondence between observable KPIs, typical measures, and the components of OEE (Availability, Performance, Quality). The table does not replace the calculation of OEE, but rather makes explicit, in a transparent way, the rationale by which proxies and flow indicators can be interpreted as plausible contributions to the components of the indicator.

KPI / Variable	Typical Measure in the Literature / Company Practice	Main Proxy	OEE Component Most Strongly Affected
Cycle time / equivalent cycle time	s/piece, min/cycle; time distribution	Cycle stability, variability reduction	Performance (<i>indirectly Availability if micro-stoppages are reduced</i>)
Throughput / line output	pieces/hour, completed cycles/shift	Output increase with unchanged resources	Performance (<i>actual capacity</i>)
Waiting times (robot/machine/operator)	min/shift, % waiting time	Lead time reduction, improved synchronization	Availability (<i>reduction of non-productive time</i>) and Performance
Micro-stoppages / short stoppages	event count; cumulative duration	Reduction of micro-stops, greater regularity	Availability (<i>loss of availability</i>)
Resource utilization (cobot/machine)	% utilization; saturation; time in automatic mode	Greater effective utilization	Performance (<i>efficient use of capacity</i>)
Bottlenecks and balancing	identification of constraints; % station saturation	Reduction of constraints, improved balancing	Performance (<i>reduction of capacity losses</i>)
Scrap/defect rate and rework	% scrap; PPM; rework/shift	Positioning repeatability; reduction of manual errors	Quality (<i>requires direct measurement for validation</i>)
Process quality (stability)	deviations, gripping errors, positioning errors	Reduction of dispersion; cycle robustness	Quality (<i>in terms of outcome stability; often measured indirectly</i>)

Table 2.1: Observable KPIs, Typical Measures, and Their Link to OEE Components (Proxies)

2.2.1 Productivity and Cycle Time in Handling Applications

The available evidence indicates that productivity benefits in collaborative cells do not arise automatically from replacing manual operations with a cobot, but rather from the joint redesign of task allocation, layout, and control logics (Colim et al., 2021). In handling applications (including pick-and-place and movements functionally related to machine tending), this implies decomposing the cycle into activities suited to the robot (repetitive movements, physically demanding operations) and activities with a higher cognitive or dexterity-related content that remain under the responsibility of the operator (Gualtieri et al., 2020; Boschetti et al., 2022).

In an industrial case study in the furniture sector, Colim et al. integrate a UR10e cobot into a pre-assembly process by automating repetitive and physically demanding activities (including glue application and above-shoulder handling tasks). The evaluation, conducted through productivity indicators (for example, output per hour) and process KPIs along the assembly line, shows an improvement in labour productivity and in the overall performance of the line downstream of the affected workstation. However, the authors also identify trade-offs related to flow reorganization (greater material handling, increased occupied area, and longer lead time), highlighting that the benefit may emerge at the system level rather than in elementary cycle time alone (Colim et al., 2021).

Overall, this evidence suggests that, in SMEs, cobot applications tend to generate benefits mainly at the system level (line/cell), making it necessary to make explicit the trade-offs associated with material flow and layout choices (Colim et al., 2021). This interpretation is also consistent with modelling results highlighting the existence of multi-objective solutions and possible trade-offs between time performance and ergonomics (Pearce et al., 2018), although such studies are not always specifically focused on SMEs or exclusively on medium-payload applications.

In summary, cobots in handling applications show improvement potential primarily at the system level, provided that material flow and task allocation are carefully redesigned. Beyond average output levels, however, process stability is also of central importance for SMEs, a topic addressed in Section 2.2.2.

2.2.2 Process Variability, OEE, and Operational Stability

Alongside average cycle time, SMEs place importance on process stability and variability reduction, aspects that affect the overall performance of resources and may be indirectly reflected in OEE. In the firms analysed by Fast-Berglund and Romero, among the KPIs considered most significant in relation to the introduction of cobots are cycle regularity (even cycle time), quality, and ergonomics, rather than the robot's maximum speed alone (Fast-Berglund and Romero, 2019). This emphasis is particularly relevant in machine tending, where synchronization between the cobot and the equipment is crucial in order to minimize idle times and micro-stoppages that would reduce availability and performance.

The available results for pick-and-place and machine-tending applications with 5-12 kg cobots are often expressed through partial indicators (for example, reductions in waiting times, micro-stoppages, and greater cycle regularity), which can be interpreted as potential contributions to OEE components; by contrast, aggregated OEE measurements are less frequent, especially in SME scenarios (Fast-Berglund and Romero, 2019; Aliev et al., 2019). Contributions such as Ronzoni et al. present design and evaluation approaches that combine stochastic simulations with throughput indicators, waiting times, and ergonomic indices, with the aim of stabilizing flow and reducing performance variability (Ronzoni et al., 2021). Although they do not provide a systematic calculation of aggregated OEE, such frameworks support the interpretation that reducing variability in handling and loading phases may contribute to improving the overall performance of the cell.

The literature discussing cobot adoption in contexts typical of SMEs (subcontracting, machine tools, multi-machine supervision) emphasizes that the expected gains in machine tending frequently derive from the reduction of non-productive times associated with loading/unloading and waiting, and from greater cycle regularity, rather than from an increase in manipulator speed. In such scenarios, performance is strongly conditioned by the quality of machine-cobot integration (I/O interfaces, constrained sequences, exception handling) and by the constraints of human-robot collaboration, which may impose speed or trajectory limitations and affect actual throughput. Consequently, in order to robustly assess the impact on OEE or its components, waiting-time and micro-stoppage indicators are particularly

relevant and, where possible, “before/after” comparisons of the actual availability of the serviced resource should be performed (Fast-Berglund et al., 2019; Fast-Berglund and Romero, 2019; Gualtieri et al., 2020; Gualtieri et al., 2021).

In conclusion, the literature indicates a potential contribution of cobots to operational stability and variability reduction, while also highlighting a gap in direct measurements of overall OEE. A further area of relevance for SMEs concerns product quality, which is addressed in Section 2.2.3.

2.2.3 Product Quality, Scrap Rate, and Variability of Outcomes

With regard to quality and scrap, studies focused on handling and machine-tending applications provide predominantly indirect evidence (Colim et al., 2021; Gualtieri et al., 2020). In the following, “quality” refers both to the reduction of defects or scrap and to process stability, which reduces rework and non-conformities; however, the literature reviewed more often reports indirect indicators of stability and repeatability than direct measures of defectiveness.

In some case studies, the automation of repetitive operations may reduce the variability associated with manual gestures and fatigue, with expected improvements in terms of process consistency; however, direct quantification of the scrap rate is not always reported (Colim et al., 2021). Consistently, the literature on Human-Robot Collaboration highlights that assigning the most physically demanding and monotonous operations to the cobot can increase repeatability and precision, with potential benefits for quality; even in this stream of research, however, systematic measurements of defectiveness and scrap with specific “before/after” comparisons for collaborative pick-and-place and machine-tending cells within the payload range considered remain rare (Gualtieri et al., 2020).

It follows that the link between manipulation repeatability and the possible reduction of process errors is plausible, but is not yet robustly and comparably supported by dedicated historical series in the literature reviewed. This gap justifies the inclusion of scrap rate and variability of outcomes explicitly among the evaluation KPIs in the following chapters, giving preference, where possible, to company-level “before/after” measurement protocols in order to make impacts comparable.

2.2.4 Ergonomics and Reduction of Biomechanical Load

From an ergonomic perspective, there is strong convergence between empirical studies and systematic reviews. Gualtieri et al. highlight that a substantial portion of the research on industrial collaborative robotics focuses on safety and ergonomics, with particular attention to the reduction of biomechanical overload in heavy and repetitive tasks (Gualtieri et al., 2020). Within this framework, pick-and-place and machine-tending applications involving medium-payload cobots are especially well suited to relieving operators of frequent load-handling tasks and awkward postures, thereby reducing risk factors for musculoskeletal disorders.

Industrial cases such as that reported by Colim et al. show significant reductions in repetitive manual actions and critical postures, with measurable improvements in ergonomic indicators and working conditions (Colim et al., 2021). Modelling studies also indicate that the reduction of biomechanical overload indices may be compatible with time-performance objectives when task allocation is optimized, highlighting the existence of trade-offs and the possibility of multi-objective solutions (Pearce et al., 2018). More recent contributions refer to control and task-balancing approaches jointly oriented toward productivity and ergonomics, confirming both the measurability of the ergonomic benefit and its integration with production KPIs (Boschetti et al., 2022).

Overall, ergonomic benefit appears, to date, to be the most robustly documented and often represents a primary motivation for investment in SMEs (Colim et al., 2021; Gualtieri et al., 2020; Pearce et al., 2018).

2.2.5 Summary of Benefits with Respect to KPIs

Overall, the literature documents stronger benefits for ergonomics and, in several cases, for productivity/throughput at the system level, whereas for aggregated OEE and scrap rate partial measures or inferences based on indirect indicators prevail. Consequently, the evidence is heterogeneous: some KPIs are directly measured in case studies, while others require “before/after” measurement protocols for robust quantification in SMEs.

On the productivity side, industrial cases report increases in labour productivity and improvements in line output compared with more manual configurations, against

trade-offs related to flow complexity and, at times, lead time (Colim et al., 2021). With regard to cycle time, the evidence suggests that the benefit is not necessarily observable at the level of the single operation, but may emerge at the system level (line/cell) through a more efficient allocation of tasks and the reduction of physically demanding or repetitive manual activities (Gualtieri et al., 2020; Colim et al., 2021).

Regarding OEE, the literature more often provides partial measures consistent with a potential improvement in flow stability and in the availability and performance components, whereas aggregated quantifications are less frequent, especially in SME scenarios (Fast-Berglund and Romero, 2019; Aliev et al., 2019; Ronzoni et al., 2021). As for quality and scrap rate, the applications considered are mainly associated, by inference, with greater repeatability and stability of handling, but direct measures of defectiveness remain limited and require dedicated company-level measurements for robust comparisons with the manual scenario (Colim et al., 2021). By contrast, ergonomic benefits are widely supported by empirical studies and reviews, which document significant reductions in exposure to repetitive tasks, awkward postures, and load-handling activities in applications where cobots replace or support the operator in the most physically demanding phases (Gualtieri et al., 2020; Colim et al., 2021; Pearce et al., 2018).

In summary, in manufacturing SMEs, pick-and-place and machine-tending applications involving medium-payload cobots show observable benefits primarily in terms of ergonomics and, in many cases, of productivity and flow stability. Quantitative evidence on aggregated OEE and scrap rate remains partial: the available results should therefore be interpreted through indirect indicators and taken as useful guidance for defining coherent evaluation metrics and protocols.

2.3 Limitations and Challenges in Cobot Integration in SMEs

Pick-and-place and machine-tending applications involving cobots represent, for many SMEs, a frequently adopted entry path into collaborative robotics. However, their diffusion is often constrained by limitations and challenges that do not depend exclusively on the manipulator, but rather on the overall integration of the cell: safety requirements, economic sustainability, available skills, and layout constraints. In

continuity with Section 2.2, this section analyses these critical issues with specific reference to pick-and-place and machine tending in manufacturing SME contexts.

2.3.1 Safety, Human Factors, and Regulatory Complexity

A first critical area concerns safety and, more generally, the management of human factors in collaborative cells. Cobots are designed to enable collaborative operating modes and the sharing of workspace with the operator; however, the literature emphasizes that the “collaborative” nature of the arm alone is not sufficient to guarantee application safety. The risk profile may change significantly when the robot is integrated into a production environment and equipped with specific EOAT and tooling, making application-specific safety measures necessary (Gualtieri et al., 2021).

Gualtieri et al. point out that the implementation of collaborative systems requires joint compliance with international standards relating to the safety of industrial robots and the ergonomic design of work environments, posing particularly significant challenges for SMEs (Gualtieri et al., 2020). The ISO/TS 15066 specification identifies four recognized modes of collaboration (safety-rated monitored stop, hand guiding, speed and separation monitoring, power and force limiting), and risk assessment proves complex because of the multiplicity of contact scenarios and the variability of mechanical risks depending on the application and the nature of human-robot interaction (Gualtieri et al., 2020).

The review by Faccio et al. confirms that physical proximity may introduce variables related to ergonomics, mental workload, trust, and risk perception: the same interaction that enables benefits may also constitute a limitation if not properly managed (Faccio et al., 2023). If these dimensions are not governed in a structured way, the presence of the cobot may generate anxiety, cognitive overload, or compensatory behaviours, thereby reducing the expected benefits and compromising operational stability and acceptance (Faccio et al., 2023).

At the application level, pick-and-place and, above all, machine tending are often implemented in modes of coexistence or synchronized interaction, with generally more limited direct contact; this may reduce the complexity of certain safety functions, but it does not eliminate the need for a detailed analysis of the risks

associated with accidental collisions, impacts with the workpiece, or crushing near fixtures and buffers (Fast-Berglund and Romero, 2019). Moreover, constraints associated with collaborative modes may affect speeds, trajectories, and cycle times, with indirect effects on performance and economic outcomes (Gualtieri et al., 2020).

In summary, pick-and-place and machine-tending applications often present a more manageable level of complexity than domains characterized by more intensive interaction, but they nonetheless require specific competences in risk assessment and human-centred design, as well as an explicit definition of the operational assumptions that affect KPIs (Gualtieri et al., 2020; Gualtieri et al., 2021; Faccio et al., 2023).

2.3.2 Economic Evaluation, TCO, and Uncertainty Regarding Benefits

A second critical area concerns the economic evaluation of cobot investments and, in particular, the ability of SMEs to estimate with sufficient reliability the expected return of applications. Fast-Berglund and Romero observe that firms show strong strategic interest in pick-and-place and load-unload applications, but also report managerial and financial obstacles, as well as difficulty in demonstrating and quantifying ROI in support of investment decisions (Fast-Berglund and Romero, 2019). This discrepancy between application priority and actual investment suggests uncertainty in the evaluation of benefits and in the criteria used to select use cases.

The literature on KPIs also highlights that robustly measuring the performance of collaborative systems (for example, cycle time, micro-stoppages, cell availability, scrap/rework) requires data collection systems, coherent indicators, and non-trivial analytical competences. Even when the application is an “entry-level” one, a reliable evaluation may require complementary investments in measurement tools and data-interpretation capabilities, which are often limited in small firms (Aliev et al., 2019).

Design-oriented studies further show that trade-offs between performance and ergonomic objectives may make the effect on production efficiency-and therefore on the economic components linked to throughput and saturation-non-univocal (Pearce et al., 2018). At the application level, industrial cases report improvements in productivity and working conditions, but also side effects (for example, increased occupied area, greater handling requirements, and longer lead time) related to

reorganization and flow management, which complicate the calculation of payback and ROI if such indirect costs are not taken into account (Colim et al., 2021). In addition, some contributions underline that a significant share of the benefits may derive from the reduction of ergonomic risk and potential injuries, dimensions that are rarely incorporated into static payback models (Ronzoni et al., 2021).

Overall, the literature suggests improvement potential, but also highlights the difficulty of translating such benefits into robust and comparable economic indicators, especially in the presence of indirect costs and “soft” benefits (ergonomics, perceived quality, stability) that require structured metrics and data.

2.3.3 Skills, Readiness, and Organizational Change Management

The introduction of cobots requires not only investment in hardware, but also an adequate base of technical and organizational competences. Fast-Berglund and Romero note that many SMEs do not possess the competences required to decide where and what to automate with cobots, highlighting the need for more structured automation strategies (Fast-Berglund and Romero, 2019). The difficulty concerns not only programming, but also the selection of suitable tasks, the assessment of impacts on processes, and the management of the organizational transition.

Pick-and-place and machine tending are often perceived as more accessible applications because, in most cases, they require less advanced perception and data integration than quality-control domains based on vision and traceability, which entail more extensive digital infrastructures and competences (Židek et al., 2020). However, the need remains central to train operators capable of working safely with the cobot and to have technical profiles dedicated to configuration, maintenance, fault diagnosis, and continuous improvement of the cells (Fast-Berglund and Romero, 2019).

The literature also emphasizes the importance of change management: in the absence of information, training, and involvement, the introduction of the cobot may encounter resistance and reduce the overall effectiveness of the intervention (Faccio et al., 2023). Human-centred approaches and advanced control systems that dynamically rebalance task allocation between human and robot may increase performance and safety, but they require advanced competences in sensing,

modelling, and multi-objective control, which are often not available internally in SMEs without external support (Boschetti et al., 2022).

In summary, even in applications considered “entry-level,” technical and organizational competences represent a significant barrier and a critical success factor for the operational sustainability of collaborative solutions.

2.3.4 Layout Constraints, Material Flow, and Cell Integration

A further critical area concerns the production layout and the physical integration of the cobot into the existing line. The literature agrees that the benefits of collaborative systems do not derive solely from replacing a manual operation with a robotic arm, but from the joint redesign of workstations, flows, and interfaces (Colim et al., 2021; Ronzoni et al., 2021).

Industrial cases show that the introduction of a cobot may require new workstations, buffers, and auxiliary devices, with impacts on occupied area, accessibility, material feeding, and the management of operating zones; these aspects may introduce non-negligible logistical complexity and indirect costs (Colim et al., 2021). Design frameworks based on flow modelling and simulation support the definition of more robust cells, but may prove burdensome in SME contexts if they require multiple tools and iterations (Ronzoni et al., 2021).

From an application perspective, pick-and-place and machine tending require repetitive trajectories and relatively well-defined pick-and-place positions; when part feeding and accessibility are managed in a basic manner, the layout may remain relatively compact. However, buffers, fixtures, safety devices, replenishment ergonomics, and maintenance space may significantly increase the overall footprint. It follows that, in existing plants (brownfield environments) with limited space and lines developed incrementally, physical and logistical constraints may limit the feasibility and scalability of collaborative solutions or require additional reorganization investments (Colim et al., 2021; Ronzoni et al., 2021).

2.3.5 Summary: Limitations, Challenges, and Implications

L'analisi dei limiti e delle sfide colloca pick-and-place e machine-tending con cobot a payload medio in una posizione intermedia: applicazioni indicate in letteratura come prioritarie e relativamente più accessibili per le PMI, ma

condizionate da criticità che richiedono una gestione strutturata (Fast-Berglund e Romero, 2019; Gualtieri et al., 2021).

Sul fronte della sicurezza, tali applicazioni beneficiano in media di livelli di interazione meno intensi, ma richiedono comunque un approccio rigoroso alla conformità normativa e alla progettazione centrata sull'operatore; inoltre, i vincoli delle modalità collaborative possono influire su tempi ciclo e throughput (Gualtieri et al., 2020; Faccio et al., 2023). Sul piano economico, i benefici possono essere significativi, ma la traduzione in ROI è spesso ostacolata da incertezza sui KPI (uso di misure parziali), da costi indiretti di layout/gestione del flusso e dalla difficoltà di contabilizzare benefici ergonomici e qualitativi (Pearce et al., 2018; Colim et al., 2021; Ronzoni et al., 2021). Per quanto riguarda le competenze, la letteratura identifica skill tecniche e capacità organizzative come barriere rilevanti per la selezione dei casi d'uso, l'integrazione stabile e la sostenibilità nel tempo (Fast-Berglund e Romero, 2019; Boschetti et al., 2022). Infine, i vincoli di layout evidenziano che l'integrazione in impianti esistenti può abilitare opportunità di ridisegno, ma anche introdurre vincoli tipici dei contesti brownfield che limitano fattibilità e scalabilità (Colim et al., 2021; Ronzoni et al., 2021).

La consapevolezza di tali limiti è essenziale per interpretare correttamente i benefici discussi nella sezione precedente e per selezionare soluzioni implementabili e sostenibili nel contesto delle PMI manifatturiere. Questi risultati motivano la necessità di definire, nei capitoli successivi, un set minimo di metriche e un protocollo di valutazione comparabile tra scenari, in grado di tradurre KPI operativi e vincoli (in particolare, safety e layout) in scelte di adozione e di investimento coerenti con le esigenze delle PMI.

Chapter 3

FROM MANUAL OPERATOR TO OPERATOR-SUPERVISOR: THE IMPACT OF COBOTS ON SKILLS, SAFETY, AND WELL-BEING

3.1 Changes in operational roles: from manual operator to “operator-supervisor”

The adoption of collaborative robots in manufacturing SMEs does not merely automate specific tasks, but reconfigures workstation-level work: the operator evolves from a manual executor into an operator-supervisor of the collaborative cell, with implications for operational responsibilities, required skills, and modes of human-robot interaction (Gualtieri et al., 2021). This transformation becomes fully evident during integration into the work system, but is largely determined already at the adoption stage, when the firm defines the deployment configuration (mode of collaboration, task allocation, and operational constraints), which in turn shapes the expected role profile and the associated organizational and safety requirements (Gualtieri et al., 2021).

In traditional systems, the worker mainly performs elementary assembly and handling operations, often characterized by high repetitiveness, physical load, and limited scope for intervention in how the task is executed (Gualtieri et al., 2021). In collaborative settings, the more physically demanding and repetitive activities are progressively assigned to the cobot, while the operator takes responsibility for managing the cell: cycle supervision, system-state monitoring, variability management, and quality control (Colim et al., 2021b; Gualtieri et al., 2021). Within this framework, collaborative robotics seeks to combine human capabilities (adaptability, dexterity, judgment) with the strengths of the machine (repeatability, precision) from a human-centred perspective (Gualtieri et al., 2021).

Empirical evidence supports this task reallocation and the resulting shift toward a supervisory role. In a case study involving the conversion of a manual workstation into a collaborative one, the redesign of the layout and the assignment of the more

physically demanding tasks to the cobot made it possible to reduce biomechanical overload and, in parallel, improve productive performance (Gualtieri et al., 2020). In addition, quantitative approaches to task allocation between operator and cobot show that it is possible to assess process performance and physical workload jointly, thereby making the trade-offs between objectives explicit (Pearce et al., 2018).

This role transformation is reflected in the structure of operational responsibilities. The operator-supervisor is required to synchronize their pace with that of the cobot, monitor its status, and intervene in the event of anomalies or stoppages, as well as manage exceptions and restore operations in accordance with defined procedures (Gualtieri et al., 2021). The collaboration models described in the literature (independent, simultaneous, sequential, supportive) presuppose a worker capable of maintaining awareness of the system state and coordinating the interaction smoothly (Colim et al., 2021b). The result is a multidimensional role that integrates non-automated manual activities, collaboration control, and exception management.

At the same time, the profile of required skills evolves. Alongside manual abilities, technical-cognitive competences become central: a basic understanding of cobot operation, the ability to interpret interfaces, states, and diagnostics, and problem-solving capability in the event of deviations from the expected cycle (Lorenzini et al., 2023). These aspects, together with the organizational conditions that support them (training, definition of operational responsibilities, and support mechanisms), are examined in greater depth in Section 3.2; the ergonomic and psychosocial implications of collaborative work are discussed in Section 3.3.

In summary, in collaborative contexts the cobot absorbs repetitive and physically demanding tasks, while the operator assumes supervisory, coordination, and exception-management functions within the cell, with a strengthening of technical-cognitive skills and of the coordination and communication requirements involved in human-robot interaction (Colim et al., 2021b; Pearce et al., 2018; Lorenzini et al., 2023).

3.2 Required Skills and Training: Basic Digital Competences and Simplified Programming

The transition from manual operator to operator-supervisor makes the skill profile required to work effectively in human-robot collaboration contexts within manufacturing SMEs a central issue. The introduction of cobots does not merely entail learning new procedures, but also a redefinition of the digital and technical-operational competences required, as well as of the training practices through which these competences are developed and consolidated (Lorenzini et al., 2023).

The evidence converges on three families of competences:

- i. basic digital literacy, necessary for interpreting states, data, and diagnostics;
- ii. technical-operational and safety competences, necessary for managing the modes, constraints, and anomalies of the collaborative system;
- iii. ergonomic-organizational/HSE competences, necessary for recognizing the implications of collaboration for workload, health, and safety, and for contributing to sustainable task-allocation choices (Gualtieri et al., 2021; Lorenzini et al., 2023).

These competences can be developed more effectively through structured and participatory training pathways, which support trust, acceptance, and the stabilization of operational practices (Colim et al., 2021a).

3.2.1 Basic Digital Skills

With regard to digital competences, the ability to read process information and interact with interfaces and operator panels is instrumental to the management of system states, diagnostics, and basic reconfigurations of the collaborative system (Lorenzini et al., 2023). From an SME perspective, the use of rapid and simplified tools to assess the suitability of collaborative solutions highlights the need to make the preliminary evaluation phase accessible even in contexts with limited resources and specialist competences (Gualtieri et al., 2020). This makes it appropriate to define a shared minimum level of digital literacy on which to build more specific collaborative robotics competences.

Alongside digital competences, the operator-supervisor role requires technical-operational and safety-related competences concerning the functioning of the robotic system and the management of interaction under both ordinary and non-routine

conditions. In practice, this includes an understanding of the operational constraints associated with collaboration (e.g., speed and force limits, operating logics, states, and transitions), as well as the management of stops, controlled restarts, and exception conditions, in accordance with procedures (Gualtieri et al., 2021). Moreover, since functional allocation and task design affect user experience and long-term well-being, it becomes important to develop ergonomic-organizational/HSE competences to recognize and prevent physical and cognitive overload (Billing et al., 2025; Lorenzini et al., 2023).

The acquisition of these competences is more effective when embedded in structured and participatory training pathways. Studies on workers' perceptions highlight positive expectations regarding ergonomic and productivity benefits, but also concerns related to accidents, mental complexity, and employment impact; in some experiences, there also emerges an initial preference for traditional segregated robots, associated with limited familiarity with robotics and with a baseline level of trust that still has to be built (Colim et al., 2021a). The same studies indicate that worker involvement and targeted training constitute essential levers for strengthening trust in safety measures and reducing barriers related to risk perception (Colim et al., 2021a).

3.2.2 Simplified Programming

Within this framework, simplified programming interfaces represent a potential enabler of autonomy, since they aim to reduce dependence on specialist competences for the use and reconfiguration of cobots. By simplified programming, we mean solutions that reduce the complexity of configuration and reconfiguration (for example, lead-through programming, guided procedures, template libraries and preset parameters, multimodal modes), whereas intuitiveness of use concerns the consistency of the interface with the user's mental models and the transparency of system behaviour (Lorenzini et al., 2023). The literature notes that, despite the development of more "intuitive" modes, lead-through programming and offline programming are still common in industrial applications; this distinction is relevant because lead-through programming partially lowers the entry barrier, whereas offline

programming is often associated with more specialist competences, making the reduction of the barrier only partial (Lorenzini et al., 2023).

In terms of learning, simplification does not eliminate the need for competences, but changes their nature and distribution: from programming at the implementation level toward guided configuration, the interpretation of feedback and diagnostics, and the management of real-time interaction (Lorenzini et al., 2023). Since mental workload and perceived stress also depend on the quality of interaction and system communication, interfaces that lack transparency may reduce the overall ergonomic benefits of HRC (Gualtieri et al., 2021; Billing et al., 2025; Lorenzini et al., 2023).

3.2.3 Section Summary

In summary, the literature outlines an expansion of the operator-supervisor's competence profile across three families (digital; technical-operational/safety; ergonomic-organizational/HSE), which can be developed more effectively through structured and participatory training pathways (Colim et al., 2021a; Lorenzini et al., 2023). Simplified programming interfaces may foster autonomy and more predictable learning times, but their effectiveness depends on alignment with the actual level of competence and on the quality of interaction design and training (Lorenzini et al., 2023). The effects on ergonomics, safety, and well-being in collaborative work are discussed in Section 3.3.

3.3 Ergonomics, Safety, and Occupational Well-Being

The introduction of cobots in manufacturing contexts can significantly affect operators' ergonomics, safety, and occupational well-being, but such effects are not intrinsic to the technology: they depend on cell-design choices, layout, and task allocation within the human-robot system (Gualtieri et al., 2021; Pearce et al., 2018).

This section synthesizes the available evidence along three interdependent dimensions:

- i. physical ergonomics and the prevention of biomechanical risks;
- ii. mechanical safety in shared spaces and safety requirements;
- iii. cognitive ergonomics and psychosocial factors, which influence stress, trust, and perceived safety and may enable or constrain the sustainability of

Human-Robot Collaboration (HRC) solutions in SMEs (Billing et al., 2025; Gualtieri et al., 2021; Lorenzini et al., 2023).

The literature on health and safety in HRC describes a dual effect. On the one hand, cobots can help reduce biomechanical overload by supporting operators in heavy and repetitive tasks; on the other hand, close collaboration may introduce psychological stress, also linked to uncertainty regarding robot behaviour, making it necessary to explicitly include aspects of cognitive ergonomics in the design of collaborative cells (Gualtieri et al., 2021).

3.3.1 *Physical Ergonomics*

If properly designed and integrated, cobots can assume or support the most physically demanding tasks, reducing exposure to awkward postures, repetitive exertion, and manual load handling, with favourable effects on the prevention of musculoskeletal disorders (Gualtieri et al., 2020; Colim et al., 2021b). In a case study involving the conversion of a manual cable-assembly workstation into a collaborative one, postural improvements measured through RULA are reported, with reductions in the overall workstation value equal to 50% (left side) and 57% (right side), together with a 12.3% reduction in cycle time (Gualtieri et al., 2020). These results indicate that, when the design explicitly aims to rebalance physical workload, it is possible to obtain ergonomic benefits and, in some cases, efficiency gains as well; at the same time, transferability depends on the tasks, production mix, space/layout constraints, and the degree of workstation redesign (Gualtieri et al., 2020).

Decision-support approaches also make it possible to make explicit the trade-off between operational performance and health protection, thereby turning ergonomics into a verifiable design constraint. Pearce et al. (2018) propose an optimization framework that generates alternative allocations between operator and cobot, simultaneously minimizing completion time (makespan) and physical strain estimated through the Strain Index, showing that the reduction of ergonomic risk can be pursued with only limited increases in cycle time (Pearce et al., 2018).

3.3.2 *Mechanical Safety and Risk Management*

The distinctive feature of HRC lies in the possible co-presence and close interaction between human and cobot, including the management of intentional or accidental contact, which requires an analysis oriented toward the specific operating scenario (layout, tasks, HRC mode, and constraints).

Recent literature shows greater attention to prevention strategies (measures acting before contact occurs) than to protection strategies (mitigation of effects after contact), including anticollision systems and adaptations in control and planning aimed at reducing the probability of impacts while maintaining adequate performance (Gualtieri et al., 2021). In operational terms, this implies an integrated approach that combines layout choices and safety strategies with procedures for controlled stop and restart, exception management, and training consistent with HRC constraints and operating modes (Gualtieri et al., 2021).

3.3.3 *Cognitive Ergonomics and Psychosocial Factors*

Beyond physical safety, cognitive ergonomics and psychosocial factors are crucial for well-being and perceived safety: mental workload, attention, the ability to anticipate system states and behaviours, stress, concerns, acceptance, and perceptions related to organizational change (Billing et al., 2025; Gualtieri et al., 2021; Lorenzini et al., 2023). From this perspective, the quality of interaction also depends on the predictability, reliability, and usability of interfaces, as well as on the system's ability to make the cobot's state and intentions "readable" (Laudante et al., 2022).

Field evidence confirms the impact of these dimensions on the acceptability and success of HRC projects. In a study on workers' perceptions regarding the transformation of manual workstations into collaborative ones, Colim et al. (2021a) identify a mix of positive expectations and concerns: anticipated benefits for working conditions and the reduction of repetitive effort, but also worries about accidents, increased mental complexity and stress, and possible impacts on employment; moreover, a proportion of participants report that they would prefer, at least initially, traditional segregated robots. The authors highlight the importance of participatory approaches (worker involvement) and targeted training in building trust and addressing barriers related to risk perception (Colim et al., 2021a).

3.3.4 *Concluding Summary*

In summary, three implications emerge. First, cobots can generate substantial improvements in physical ergonomics and a reduction in biomechanical risks when integration takes place in workstations redesigned according to human-centred criteria and with task allocation oriented toward balancing productivity and physical workload (Gualtieri et al., 2020; Pearce et al., 2018; Colim et al., 2021b). Second, safety in HRC requires an integrated approach that combines prevention strategies, layout design, operating procedures, and training consistent with the specific scenario (Gualtieri et al., 2021). Third, physical benefits may be undermined if cognitive ergonomics and psychosocial factors (trust, risk perception, mental workload, and stress), which are decisive for the acceptability and sustainability of collaborative solutions, are not adequately addressed (Billing et al., 2025; Gualtieri et al., 2021; Colim et al., 2021a).

For the purposes of this thesis, this implies that the introduction of cobots in SMEs supports the transition toward an operator-supervisor role, but that this transition yields sustainable benefits only if it is supported by coherent task-allocation choices, user-centred cell design, and the development of appropriate competences (Gualtieri et al., 2021; Billing et al., 2025; Lorenzini et al., 2023).

Chapter 4

ECONOMIC EVALUATION OF THE ADOPTION OF COLLABORATIVE ROBOTS IN MANUFACTURING SMEs

4.1 Cost Structure in Collaborative Robot Projects in SMEs

This section illustrates how the adoption of collaborative robots in manufacturing SMEs modifies the structure of capital expenditure (CAPEX) and operating expenditure (OPEX) relative to manual labour and traditional industrial robotics. The aim is to identify and systematically classify the main cost items (cobot, end-effector, vision systems, safety, engineering/integration, and training), while also including recurring operating costs (energy, maintenance, residual labour, and set-up/reconfiguration). The joint recomposition of CAPEX and OPEX defines the economic scope within which alternatives can be compared and the overall sustainability of the project can be evaluated.

To ensure consistency in the analyses, the following convention is adopted, in line with approaches that distinguish between initial investment and operating cash flows (Gusan et al., 2021; Țîțu et al., 2024):

- CAPEX: one-off costs required to bring the cell into operation (hardware purchase, supports and tooling, installation and initial integration, safety implementation, initial training).
- OPEX: recurring costs over the useful life of the system (energy, maintenance and restoration, updates and reprogramming, residual labour cost, set-up, changeover, and reconfiguration costs, where relevant to the production context).

The price of the cobot therefore represents only one component of the investment: application cases and cost models show that the investment typically includes the robot, supports and structures, gripping devices, auxiliary components, and safety equipment, in addition to implementation costs related to the resources employed for integration (Gusan et al., 2021; Țîțu et al., 2024). It follows that the economic

sustainability of a project in SMEs depends on the overall integration of CAPEX and OPEX, rather than on the price of the robot alone.

4.1.1 *Investment Costs of the Cobot and Main Hardware*

With regard to cobots and the main hardware components, application cases and cost models make it possible to outline an order of magnitude for the capital required. In an application involving two UR10e units, Țîțu et al. (2024) estimate the indirect costs (hardware) as the sum of the price of the robots ($2 \times \text{€}28,000$), support structures ($2 \times \text{€}4,000$), grippers ($2 \times \text{€}1,500$), the safety control box ($\text{€}1,800$), perimeter scanners ($5 \times \text{€}1,618$), and auxiliary components ($\text{€}5,000$), obtaining a hardware cost of $\text{€}81,890$, a figure that rises to $\text{€}85,594.36$ when direct implementation costs are included (Țîțu et al., 2024).

In another application, Gusan et al. (2021) report, for a single UR10, a cobot price of $\text{€}25,000$, a metal structure costing $\text{€}3,000$, and a safety system costing $\text{€}5,000$, reaching a total investment of $\text{€}36,970$ in the scenario considered (Gusan et al., 2021). At plant scale, Ceve (2024) describes a case in the automotive sector involving ten UR10 units ($\text{\$}35,000$ per unit) and additional items for gripping devices, training, and integration, as well as planned maintenance, for a total investment of $\text{\$}566,000$ (Ceve, 2024).

Overall, this evidence places the CAPEX of the cobot as the “machine body” in the order of approximately $\text{€}25,000\text{--}28,000$ per unit in the sources expressed in euros (Gusan et al., 2021; Țîțu et al., 2024), and approximately $\text{\$}35,000$ per unit in the source expressed in dollars (Ceve, 2024). These amounts are consistently supplemented by costs for supports and structures, safety, and auxiliary components, the incidence of which varies depending on the cost scope included (hardware vs hardware plus implementation) and on the application requirements (Gusan et al., 2021; Țîțu et al., 2024). Since the sources adopt different currencies and base years, these values are used as orders of magnitude rather than as a basis for direct comparison across non-homogeneous studies.

4.1.2 *End-Effectors and Vision Systems*

End-effectors (EOAT) represent a relevant cost component and are closely linked to the application feasibility and operational flexibility of the cell. In the case

analysed by Țîțu et al. (2024), the grippers are valued at €1,500 each (Țîțu et al., 2024). In the context reported by Ceve (2024), more advanced gripping devices reach unit values in the order of \$5,000 and \$8,000, highlighting how the choice of EOAT can significantly increase CAPEX (Ceve, 2024).

In addition to EOAT, some applications may require perception systems, for example vision systems, which entail additional CAPEX (hardware, software, and integration). In high-variety contexts with small or medium batch sizes, EOAT and, where necessary, vision systems must be assessed jointly with the operating costs of set-up, changeover, and reconfiguration (technical time and downtime), which increase with the frequency of changeovers and the average reconfiguration time.

4.1.3 Safety Systems and Cell Configuration

Safety systems constitute a significant cost category, with configurations that differ between collaborative solutions and traditional industrial robotics. In the case involving two UR10e units, Țîțu et al. (2024) include a safety control box costing €1,800 and perimeter scanners ($5 \times €1,618$), highlighting a substantial share of expenditure associated with sensing and safety control (Țîțu et al., 2024). Gusan et al. (2021) estimate €5,000 for a safety system (safety PLC and scanner) associated with a UR10 (Gusan et al., 2021).

In comparison with a traditional industrial solution, Țîțu et al. (2024) show that integration may require a dedicated cell: in the case analysed, the cell is estimated at €50,000, and the total indirect costs for the industrial configuration reach €165,000 (Țîțu et al., 2024). It follows that, in traditional configurations, the cell may absorb a substantial share of total CAPEX, whereas in collaborative solutions expenditure tends to be distributed across devices, control systems, and auxiliary components, depending on the design solution adopted (Gusan et al., 2021; Țîțu et al., 2024). Consistent with the structure of the model, the estimation of safety costs is linked to the preliminary risk assessment (RA) of the scenario under consideration.

4.1.4 Engineering, Integration, and Training Costs

In addition to hardware costs, engineering, integration, and training costs are also significant, and are often critical for SMEs with limited internal competences. In the model proposed by Țîțu et al. (2024), direct implementation costs include hours of

project management, electromechanical technician work, and programming, as well as energy consumption associated with the implementation phase (Țîțu et al., 2024). In the case reported by Ceve (2024), the project plan includes a specific item for training and integration (Ceve, 2024).

In line with the formalization of the model, integration costs (for example, cell/PLC/interfacing and engineering hours) are treated as a separate item and are often underestimated during the preliminary evaluation phase. Consistent with the CAPEX/OPEX distinction, initial training and the integration required for go-live are considered CAPEX. By contrast, recurring reprogramming activities and training updates required for new variants or products are treated as OPEX.

4.1.5 Operating Costs: Energy, Labour, Maintenance, and Set-Up

Among recurring operating costs, the literature includes energy, residual labour, and maintenance or operational services. With regard to energy, Gusan et al. (2021), in the economic calculation they present, consider an estimate of the cobot's annual energy consumption and compare this item with that associated with the industrial solution, while maintaining the same hypothesis framework (Gusan et al., 2021). In a comparison between collaborative implementation and implementation with industrial robots, Țîțu et al. (2024) report annual energy consumption that is much lower for the collaborative solution than for the industrial configuration considered (Țîțu et al., 2024). Overall, this evidence suggests that the energy-related OPEX of cobots may be relatively limited compared with other operating components, while still depending on annual operating hours and the utilization profile (Gusan et al., 2021; Țîțu et al., 2024).

With regard to maintenance and operational overheads, Calvo and Gil (2022) note that the costs required to keep the automation operational (including programming and maintenance) must be taken into account in the economic representation of the system (Calvo and Gil, 2022). In SME contexts, a further share of OPEX may derive from set-up, changeover, and reconfiguration, as well as from losses in availability/efficiency and waiting times that affect actual cycle times and throughput; these components tend to increase as variability and the frequency of changeovers rise.

4.1.6 Summary and Implications for Economic Evaluation

Overall, the cost structure for cobot adoption in SMEs includes CAPEX distributed across the robot, EOAT, safety, and auxiliary components, in addition to one-off integration and initial training costs, and OPEX associated with energy consumption, maintenance, programming, and the cost of residual labour, as well as, where relevant, set-up, changeover, and reconfiguration costs. In comparison with traditional alternatives, cell configuration and safety measures may substantially affect the investment profile, whereas the intensity of use (annual operating hours or shifts), production variability (batch sizes and frequency of changeovers), and operational overheads condition recurring costs (Calvo and Gil, 2022; Gusan et al., 2021; Țîțu et al., 2024). Where appropriate, the analysis of economic flows may be complemented by discounting (NPV), with a discount rate explicitly stated and consistent with the firm's context. On this basis, Section 4.3 formalizes the economic evaluation indicators and models consistent with SME contexts.

4.2 Economic Benefits of Collaborative Robots in Manufacturing SMEs

This section analyses the economic benefits deriving from the adoption of collaborative robots in manufacturing SMEs, in terms of increased productivity, greater operational continuity, improved quality, and the reduction of ergonomic and injury-related costs, in comparison with manual solutions or traditional automation. An assessment of economic convenience cannot be reduced solely to the containment of CAPEX/OPEX, but requires a multidimensional analysis that includes operational, technological, and human variables (including quality, safety, and ergonomics), also because part of the benefits, particularly those related to ergonomics, is difficult to quantify without explicit proxies (Silva et al., 2022; Salimbeni & Mamani, 2020). From this perspective, cobots are discussed as a technology useful for managing contexts characterized by high variety, pressure on lead times and batch sizes, and the need for adaptability in production systems (Silva et al., 2022; Salimbeni & Mamani, 2020).

Within the framework of Chapter 5, economic benefits are interpreted jointly with the constraints of the work and safety system (safety/work system): collaborative requirements (for example, zones, speeds, and separation distances) and a

preliminary RA (screening) make it possible to define traceable operational assumptions, which affect throughput, time, and costs and, therefore, economic outputs (ROI, payback, and TCO). The following subsections systematically examine productivity and operational continuity, quality and scrap reduction, and ergonomics.

4.2.1 *Productivity and Operational Continuity*

A first dimension concerns productivity and operational continuity in comparison with manual solutions. In the literature, productivity is addressed through indicators such as cycle time and flow time, as well as measures of labour efficiency (for example, good units per labour hour); operational performance also depends on organizational and utilization-related factors (annual operating hours, saturation) that condition the actual economic value generated (Silva et al., 2022).

In the documented cases, performance improvements may be reflected in more favourable ROI and payback, provided that the assumptions regarding utilization and performance are realistic. Ceve (2024) reports, for the SEAT Componentes case, economic-financial indicators, including ROI and payback, associated with the introduction of ten UR10 units; the transferability of this evidence to SME contexts is more robust when the utilization and saturation logic applies under comparable operating conditions (Ceve, 2024). In a comparison between a manual scenario and a cobot-based scenario, Gusan et al. (2021) quantify cumulative savings over the period considered (Gusan et al., 2021).

However, the effect on productivity is not univocal: cobots often operate under speed constraints related to the safety requirements of human-robot collaboration and, therefore, productivity may constitute either an advantage or a disadvantage depending on the application and operating conditions (Silva et al., 2022). Variables such as saturation (annual operating hours), non-value-added time (for example, loading/unloading), process stability, and safety requirements directly affect the achievable output and the resulting economic benefit (Silva et al., 2022). Moreover, the possible extension of operating hours with reduced supervision is plausible above all in low-variability activities, with reliable part/material feeding and robust exception handling: conditions that limit the need for continuous operator

intervention (Silva et al., 2022). In the model, these collaborative constraints are made explicit in the process assumptions and linked to operational KPIs (throughput, times, WIP), which feed into the monetization of benefits in the economic block.

In summary, cobots generate economic benefits when they increase output per unit of labour and/or improve the effective utilization of the plant; these effects depend primarily on safety constraints and on utilization assumptions consistent with the production context (Silva et al., 2022).

4.2.2 Process Quality and Scrap Reduction

A second dimension concerns quality and scrap reduction, which can be translated into lower costs of poor quality. Quality is identified as one of the relevant benefit dimensions in decision-making models for cobot adoption, together with process-success indicators such as the success rate (Silva et al., 2022). Consistently, Salimbeni & Mamani (2020) include “quality” among the dimensions of the evaluation framework for cobot incorporation, alongside technical, ergonomic, economic-financial, and regulatory aspects (Salimbeni & Mamani, 2020).

In tasks with tight tolerances, quality stability also depends on technical adequacy: cobot repeatability, in relation to tolerances and quality criteria, and the configuration of EOAT/fixtures may constitute enabling conditions for achieving a stable reduction in scrap and defectiveness.

Quality is often less straightforward to monetize than labour savings; however, when the process is dominated by repetitive manual defects, greater standardization may reduce scrap and rework, with appreciable economic impacts (Silva et al., 2022). In summary, quality and scrap reduction represent potentially significant economic benefits, but they require explicit monetization rules in order to be properly incorporated into economic models (Silva et al., 2022; Salimbeni & Mamani, 2020).

4.2.3 Ergonomic Benefits and Reduction of Ergonomic Costs

A third dimension concerns ergonomics, musculoskeletal disorders (MSDs), injuries, and absenteeism. Ergonomics is identified among the main benefits considered in decision-making models for cobot adoption and can be assessed through ergonomic scales and indicators; moreover, the literature associates MSDs

with related costs such as absenteeism and medical or insurance expenses (Silva et al., 2022).

Ergonomic benefits may be underestimated because they are less visible in the short term within departmental costs; however, they may be reflected in operational continuity and actual productivity through reduced absenteeism and risk mitigation (Silva et al., 2022). From this perspective, Bogataj et al. (2017) propose an economic interpretation of “ergonomic investment,” showing how investments in robots (including collaborative approaches) may influence discounted evaluations, including net present value (NPV), in a supply-chain context characterized by an ageing and highly skilled workforce (Bogataj et al., 2017).

In summary, cobots may be configured as ergonomic investments that strengthen economic and social sustainability, provided that the value channels involved and their related monetization are made explicit in decision-making models (Bogataj et al., 2017; Silva et al., 2022).

4.2.4 Summary of Benefits and Link to Economic Evaluation

Considering productivity/continuity, quality, and ergonomics, it emerges that cobots can generate integrated economic benefits that go beyond labour savings alone, encompassing operational and human dimensions explicitly referred to in adoption criteria (Silva et al., 2022; Salimbeni & Mamani, 2020). The results, however, depend on assumptions regarding utilization, safety constraints, and application conditions, and productivity does not necessarily represent an advantage in every context (Silva et al., 2022).

In Section 4.3, the benefits are translated into cash flows for the calculation of ROI and payback. The results are also compared through a TCO structure over a horizon of N , complemented by sensitivity analyses on critical variables (volumes, cycle times, useful life, labour cost, and the impacts of safety and training). Relative to manual operation, the benefits arise above all from process stabilization, the reduction of poor quality, and the mitigation of ergonomic and injury-related costs affecting operational continuity (Silva et al., 2022). Relative to traditional automation, cobots are generally more competitive when flexibility and frequent reconfiguration are required and when safety and production-capacity constraints are

compatible with the expected volumes (Silva et al., 2022; Salimbeni & Mamani, 2020). In the model, this comparison is implemented as a comparison among configuration alternatives (manual baseline and cobot integration configurations, including coexistence/separation options) that are admissible through the evaluation gates and consistent with work-system and safety constraints.

4.3 Economic Evaluation Models for Cobot Adoption in SMEs

Having defined the cost structure (CAPEX/OPEX) and the main benefits, this section addresses the economic evaluation of cobot adoption in SMEs, comparing it with manual solutions and with traditional automation. By traditional automation, we mean non-collaborative solutions based on human-machine separation; this category includes, by way of example, fenced cells or dedicated lines with industrial robots, including architectures based on SCARA robots, for which safety, layout, and integration requirements typically differ from those of collaborative applications. The analysis is developed with attention to multi-shift scenarios (different annual operating hours and saturation levels) and to small production batches (frequency of changeover and reconfiguration).

This section pursues two objectives:

1. to clarify the role, meaning, and limitations of the main economic indicators used in the literature (ROI, payback, TCO, and NPV);
2. to show how costs and benefits (Sections 4.1-4.2) can be translated into coherent cash flows for quantitative comparisons across scenarios, while ensuring consistency in the operating assumptions (multi-shift operation and small batches).

4.3.1 Model Assumptions and Cash-Flow Structure

In order to make ROI, payback, TCO, and NPV comparable in SME scenarios, the following assumptions and related parameters are made explicit, to be estimated case by case using company data or literature-based ranges (Calvo and Gil, 2022; Polonara et al., 2024; Silva et al., 2022). Throughout this section, an incremental approach is adopted relative to a baseline scenario (manual or traditional

automation), assuming the same expected operational objectives (target volumes and quality).

From an application perspective, the metrics are used with complementary roles: ROI and payback as screening indicators and decision-friendly measures (often preferred by SMEs because of liquidity constraints, attention to time-to-return, and limited data availability), TCO as a measure of life-cycle cost for cost comparisons under equivalent service/productivity objectives, and NPV as a dynamic metric for long-term comparisons, when cost of capital and the temporal profile of cash flows influence the decision (Calvo and Gil, 2022; Polonara et al., 2024).

1. Evaluation horizon and useful life
 - Evaluation horizon N [years], defined according to the expected useful life and documented in the decision dossier; typically $N \leq T$.
 - Economic useful life T [years] of the system and any residual value (if included in the calculations).
2. Utilization and work organization (multi-shift)
 - Number of shifts, annual available hours, and utilization/saturation rate $u \in [0, 1]$ (including micro-stoppages and non-productive time).
 - “1-shift / 2-shift / 3-shift” scenarios for sensitivity analysis (Calvo and Gil, 2022).
3. Mix and batches (small batches)
 - Changeover frequency f_{ch} [changes/year] and average reconfiguration time t_{ch} [hours/change], including end-effector change, vision calibration, and quality testing (Polonara et al., 2024).
4. CAPEX/OPEX rules
 - CAPEX: initial investment required for go-live (robot, accessories, safety, integration, and initial training), in line with the classification proposed in Section 4.1.
 - OPEX: energy, maintenance, consumables, residual labour, recurring reprogramming/training, and changeover costs (Silva et al., 2022; Polonara et al., 2024).

5. Currencies and comparability

- The numerical values drawn from case studies may be expressed in different currencies (€; \$) and refer to different base years; in this chapter, they are used as orders of magnitude and as parametric ranges, avoiding direct comparisons across non-homogeneous studies.
- In the model's application calculations, monetary quantities are expressed in a single currency (EUR) and referred to a base year consistent with the company data.

4.3.1.1 Unified Mapping of Costs/Benefits to Cash Flows

The economic evaluation is reduced to a standard structure of incremental cash flows.

- Initial investment ($CAPEX_0$)

$$CAPEX_0 = C_{robot} + C_{EOAT} + C_{vision} + C_{safety} + C_{layout} + C_{integ} + C_{train}$$

- Annual operating costs ($OPEX_t$)

$$OPEX_t = C_{energy,t} + C_{maint,t} + C_{cons,t} + C_{lab,res,t} + C_{ch,t} + C_{over,t}$$

where $C_{ch,t}$ represents the annual changeover cost (operator time and loss of capacity), which is relevant in small-batch production (Polonara et al., 2024).

- Annual monetized benefits (BEN_t)

$$BEN_t = B_{lab,t} + B_{qual,t} + B_{uptime,t} + B_{ergo,t}$$

- Incremental cash flows

$$CF_0 = -CAPEX_0, \quad CF_t = BEN_t - OPEX_t \quad (t = 1, \dots, N)$$

This structure makes it possible to calculate consistently:

- Payback period:

$$\min t \text{ such that } \sum_{k=0}^t CF_k \geq 0, \quad t \leq N$$

- Cumulative ROI over horizon N :

$$ROI_{cum} = \frac{\sum_{t=1}^N CF_t}{CAPEX_0}$$

and, alternatively, average annual ROI:

$$ROI_{ann} = \frac{\overline{CF}}{CAPEX_0}, \quad \overline{CF} = \frac{1}{N} \sum_{t=1}^N CF_t$$

- TCO (operational definition):

$$TCO = CAPEX + \sum_{t=1}^N OPEX_t$$

- NPV (dynamic interpretation):

$$NPV = \sum_{t=0}^N \frac{CF_t}{(1+r)^t}$$

where r is the discount rate consistent with the cost of capital (Calvo and Gil, 2022).

In the following, for the sake of application consistency and adherence to SME decision-making practices, TCO is calculated in non-discounted form, that is, as the nominal sum of $CAPEX_0$ and $OPEX_t$ over the horizon N ; where it is necessary to take the time value of money into account, the analysis is complemented by NPV.

In the decision-making model (Chapter 5), the quantitative indicators (TCO, payback, and ROI) are used both for screening and as inputs to multicriteria scoring among admissible alternatives.

During the preliminary screening phase, where cash flows cannot be estimated reliably, a payback proxy ($CAPEX_0/\text{beneficio annuo}$) may be used exclusively as an indicative measure, provided that the assumptions are made explicit and the analysis is accompanied by sensitivity testing on the critical variables.

4.3.1.2 “Minimum” Monetization of Quality and Ergonomics

To prevent quality and ergonomics from remaining exclusively qualitative dimensions, the model adopts standard economic proxies. In the following, Δ denotes a variation relative to the baseline (absolute or relative), to be made explicit and documented in the decision dossier according to data availability and the level of measurement.

- Quality (scrap and rework)

$$B_{qual,t} = \Delta s \cdot V_t \cdot c_{scrap} + \Delta r \cdot V_t \cdot t_{rework} \cdot c_{hour} + \Delta recl_t \cdot c_{recl}$$

where Δs is the variation in scrap rate, V_t is the annual volume, and c_{scrap} is the average cost of the scrapped part; Δr is the variation in rework, t_{rework} is the average rework time, and c_{hour} is the hourly cost; $\Delta recl_t$ is the variation in claims, with average cost c_{recl} (Silva et al., 2022).

- Ergonomics (absenteeism, injuries, turnover)

$$B_{ergo,t} = \Delta d_t \cdot c_{day} + \Delta inj_t \cdot c_{inj} + \Delta turn_t \cdot c_{rep}$$

where Δd_t is the variation in days of absence, and c_{day} is the cost per day; Δinj_t is the variation in injuries, with average cost c_{inj} ; $\Delta turn_t$ is the variation in turnover, with replacement/training cost c_{rep} (Bogataj et al., 2017; Silva et al., 2022).

These proxies make it possible to systematically include quality and ergonomics in the economic comparison even when company data are incomplete, while making the monetization assumptions explicit (Silva et al., 2022).

4.3.1.3 Systematic Comparison with Traditional Automation (Common Criteria)

To make the comparison “manual vs cobot vs traditional automation” homogeneous, the model adopts four technical-economic criteria recurrent in the literature:

1. throughput and safety constraints of the work system (speed/operational limitations in the presence of the operator) (Silva et al., 2022);
2. cell and safety/layout costs (barriers/fencing and integration) (Silva et al., 2022);
3. flexibility and changeover cost (mix/batch size and recurring set-up) (Polonara et al., 2024);
4. skills and management overheads (programming, training, and maintenance) (Silva et al., 2022; Calvo and Gil, 2022).

These criteria define a minimum set of common assumptions for constructing comparable scenarios and interpreting the economic results as a function of the operational drivers.

4.3.2 Static Indicators: ROI and Payback in the Comparison among Cobots, Manual Labour, and Traditional Automation

A first family of approaches uses ROI and payback as the main evaluation tools. These indicators are attractive for SMEs because they are immediate and can be calculated from available cost and savings data; moreover, they are frequently employed as first-stage evaluation (screening) metrics in the cases analysed in the literature (Polonara et al., 2024).

In the comparison among three scenarios (manual, traditional non-collaborative automation, and cobot), the economic results depend sensitively on the combination of CAPEX, consumption, and organizational assumptions adopted in the scenario (Gusan et al., 2021). In particular, in small-batch production, system saturation and changeover cost are decisive for ROI and payback (Polonara et al., 2024).

At the same time, ROI and payback may overestimate economic convenience if they do not include recurring changeover costs, assume unrealistically high saturation, monetize only labour savings while neglecting quality and ergonomics, or ignore the time value of money in long-horizon decisions (Calvo and Gil, 2022; Silva et al., 2022). For this reason, when the horizon and cash-flow profiles require it, these indicators are complemented by a dynamic interpretation through NPV.

4.3.3 *Parametric Models and NPV Interpretation: Dynamic Evaluation and Cost of Capital*

A second family of approaches adopts parametric models that can be traced back to NPV, incorporating life horizon and cost of capital. Calvo and Gil (2022) propose parametric models based on process time saving/productivity gain and show the dependence of convenience thresholds on wages, shifts, and discount rate (Calvo and Gil, 2022). Bogataj et al. (2017) adopt a present-value-oriented approach to evaluate ergonomic investments, discussing how such interventions may affect NPV from a supply-chain perspective (Bogataj et al., 2017).

When the cost of capital is relevant or the evaluation horizon extends over multiple years, NPV is calculated as:

$$NPV = \sum_{t=0}^N \frac{CF_t}{(1+r)^t}$$

where r is the discount rate consistent with the cost of capital.

NPV models facilitate the integration of quality/ergonomics and multi-shift scenarios, but require data and quantitative competences that may be lacking in SMEs. The decision-making model proposed here reduces this barrier by introducing proxies (4.3.0.2) and scenario analyses based on a limited set of key parameters (Calvo and Gil, 2022; Silva et al., 2022).

4.3.4 TCO Perspective and Life-Cycle Comparison

The Total Cost of Ownership (TCO) perspective emerges in studies that combine CAPEX and OPEX over multi-year horizons. From an SME perspective, this view is particularly relevant when safety and layout affect the CAPEX of the industrial solution, energy costs become significant in multi-shift scenarios, and changeover costs have an impact in small-batch production (Calvo and Gil, 2022; Polonara et al., 2024; Silva et al., 2022). At the same time, the inclusion of quality and ergonomics makes it possible to capture indirect components that may emerge over the long term (Bogataj et al., 2017; Silva et al., 2022).

4.3.5 Multi-Shift Scenarios and Small Batches: Impact on Economic Results and Robustness

A cross-cutting element is represented by the sensitivity of economic results to utilization (shifts/annual operating hours) and batch size. In parametric models, the explicit inclusion of the number of shifts and available hours makes it clear that, for the same annual system cost, greater utilization allows costs to be distributed more effectively and reduces the minimum productivity thresholds required (Calvo and Gil, 2022). Complementarily, in small-batch production, economic convenience depends on the management of variants and on the reduction of reconfiguration times and impacts (flexible EOAT, vision, buffers), with effects on actual throughput and changeover cost (Polonara et al., 2024). In addition, safety constraints may limit speed and throughput in collaborative mode, making the modelling of realistic scenarios necessary (Silva et al., 2022).

In multi-shift scenarios, the increase in annual operating hours tends to improve ROI and payback for all alternatives; however, the ranking depends on the trade-off between CAPEX (often higher in traditional automation) and OPEX/operational overheads. In small-batch scenarios, the discriminating driver becomes the recurring cost of changeover and the associated loss of capacity: under these conditions, TCO (for life-cycle interpretation) and NPV (when the horizon is multi-year and the cash-flow profile differs) prove more effective in capturing indirect costs and temporal differences that may not emerge in analyses based exclusively on ROI and payback (Calvo and Gil, 2022; Polonara et al., 2024; Silva et al., 2022).

The operating assumptions used in the calculations are verified through the validation protocol discussed in the model-validation section of Chapter 5, in coherence with the process KPIs (for example, throughput/output, WIP, lead time, resource utilization), so as to consistently support the economic assumptions and robustness analyses. In the event of closely ranked alternatives in the scoring, the decision rule gives priority to the alternative that is more robust with respect to the critical assumptions; where robustness is equal, preference is given first to the lower TCO and subsequently to the shorter payback, with the rationale recorded in the decision dossier. In the following chapter, the model is applied to alternative scenarios (manual, cobot, traditional automation) in order to quantify the economic outcome as multi-shift operation and small-batch production vary, and to support the choice through multicriteria scoring applied only to admissible alternatives.

Chapter 5

DECISION-MAKING MODEL FOR THE ADOPTION AND INTEGRATION OF COBOTS IN MANUFACTURING SMEs

The aim of this chapter is to identify and systematically organize the factors influencing decisions on the adoption of collaborative robots (cobots) in manufacturing SMEs and to translate them into an operational decision-making model that integrates technical, economic, and organizational dimensions. The model is designed to support investment and configuration decisions, for example with respect to the type of HRC cell, the minimum technical requirements, and the organizational readiness conditions, thereby fostering a transparent, traceable, and replicable decision-making process.

The expected outcome of the chapter is the development of a model package consisting of:

- a conceptual framework linking the determinants and gaps identified in the literature to the model's design requirements;
- an operational model, structured as a Gate + Scoring flow, a decision rule, a checklist, and a decision dossier;
- a user guide (standard operating procedure, SOP), including scope, assumptions, and limitations;
- quality criteria and a conceptual verification of the model in the absence of an application case;
- a replicable empirical validation plan, not carried out in the present work and deferred to future developments.

In the present dissertation, empirical validation through simulation or case study is not conducted due to the absence of an available application context. Consequently, the contribution of the chapter does not lie in the empirical demonstration of the model's effectiveness, but rather in the design and conceptual verification of a formalized decision-making device. Consistent with this approach, the contribution is

assessed primarily in terms of feasibility, internal consistency, traceability, and conceptual robustness of the decision-making process, and is accompanied by a validation plan aimed at strengthening its external validity in future applications.

This delimitation of the methodological scope is also relevant for the proper academic framing of the chapter. From a decision-model design perspective, the quality of the contribution does not necessarily depend on the immediate availability of field experimentation, but rather on the ability to construct a conceptually sound device, logically coherent, formalized in a replicable manner, and oriented toward subsequent empirical verification. In this sense, the chapter represents the concluding outcome of the thesis path on a design and argumentative level, while deferring validation in real-world contexts to future developments.

Section 5.1 synthesizes and compares the literature on the drivers and constraints of adoption according to the TOE (Technology-Organization-Environment) logic and interprets the decision as a process through a dynamic lens of sensing, seizing, and reconfiguring, adopted here as the theoretical key of the chapter. Section 5.2 presents the operational decision-making model (Gate + Scoring) and its related technical, economic, and organizational blocks, integrated with checklists and SOPs. Section 5.3 defines the conceptual verification of the model in the absence of an application case. Section 5.4 formalizes the replicable empirical validation plan, based on simulation and/or case study.

5.1 Determinants of Adoption and Model Design Requirements

This section organizes the determinants of cobot adoption in manufacturing SMEs according to the TOE framework and, in parallel, interprets the decision as a process that unfolds over time. From this perspective, TOE provides the classification of the relevant factors (technological, organizational, and environmental) while the dynamic interpretive lens adopted in this chapter makes it possible to link these determinants to the firm's ability to transform an initial decision into a stable integration consistent with the work system. The section culminates in the derivation of measurable design requirements, which provide the link to the decision-making model presented in Section 5.2 and to the verification and validation procedures outlined in Sections 5.3 and 5.4.

In the present work, two analytical levels are distinguished. *Adoption* refers to the investment and configuration decision, that is, the selection of the alternative and the formalization of the operating assumptions for its use. *Integration*, by contrast, refers to the implementation process and the subsequent stabilization within the work system, which includes layout, task allocation, the safety/work system, competencies, and organizational routines. The proposed framework supports adoption, but incorporates technical, organizational, and safety constraints, as well as readiness requirements, with the aim of increasing the probability of stable integration consistent with the work system (Kopp et al., 2021; Zemlyak et al., 2022).

The adoption of cobots in manufacturing SMEs is influenced by an interdependent set of technological, organizational, and environmental factors that can be traced back to the TOE framework (Correia Simões et al., 2020). However, the presence of favorable conditions does not in itself guarantee an effective outcome. Available evidence suggests, in fact, that results and sustainability depend on the firm's ability to govern the transition across the decision-making and implementation phases, including socio-technical and human-centered dimensions (Kopp et al., 2021; Zemlyak et al., 2022). It follows that cobot selection constitutes a necessary but not sufficient condition: success depends on how that choice is translated into a deployment configuration consistent with the work system, including layout, operating modes, and safety constraints.

A recurring issue in the literature is the gap between decision-making practices and the socio-technical requirements of integration. Relevant benefits and constraints, such as safety, ergonomics, work redesign, acceptance, and trust, are often difficult to monetize and, if neglected, may compromise the outcome of implementation. Moreover, in collaborative configurations, observed performance depends on the operating conditions and HRC constraints, which may affect speed, cycle times, and effective capacity. It is therefore necessary to organize the determinants of adoption critically, highlighting their convergences, tensions, and limits of generalizability, in order to derive design requirements applicable to SMEs (Silva et al., 2022; Silva et al., 2024; Kopp et al., 2021).

5.1.1 Technological Factors: Task Suitability, HRC Constraints, and Risk of Obsolescence

From a technological perspective, adoption depends on the cobot's ability to meet the requirements of the process and the task, as well as to integrate into existing layouts and production flows. Attributes such as speed, portability, required workspace, and flexibility/reconfigurability influence the propensity for adoption (Correia Simões et al., 2020). The literature nevertheless suggests avoiding a linear interpretation of the relationship between technology and productivity. In HRC contexts, productivity must be assessed in a contextualized and task-oriented manner, since collaborative constraints and safety measures directly affect operating conditions (Silva et al., 2022; Silva et al., 2024).

A technical selection based exclusively on specifications facilitates comparability among alternatives, but may underestimate the fact that actual performance depends on the real deployment configuration within the human-robot system: task allocation, EOAT and gripping mode, definition of workspaces and layout, safety settings, and the collaborative modes adopted. Performance and safety should not be treated as independent dimensions. In HRC configurations, safety introduces a trade-off that must be made explicit in the operating assumptions, for example in terms of throughput and cycle times, in order to avoid unrealistic expectations (Silva et al., 2022; Silva et al., 2024).

In addition to immediate attributes, some contributions emphasize the dynamic dimension of innovation. The rate of technological improvement affects the perceived useful life and may influence the timing of the decision, making the risk of obsolescence a relevant element in investment appraisal (Cohen et al., 2019). Consistently, the degree of technological novelty may influence the intention to adopt also through perceived uncertainty (Correia Simões et al., 2020). For SMEs, this entails an additional trade-off: excessively innovative solutions may increase risk and integration complexity, whereas overly conservative options may reduce flexibility or generate forms of technological lock-in.

5.1.2 Organizational Factors: Readiness, Work Design, and Acceptance

From an organizational perspective, adoption depends on the firm's ability to mobilize resources and competencies and to manage change, including process

redesign and the management of work-related implications. Readiness for change and organizational and technological preparedness are central, since the introduction of new technologies requires both adequate competencies and the adaptation of existing technologies and routines (Correia Simões et al., 2020; Zemlyak et al., 2022). Complementarily, decision-making frameworks that integrate quantitative and qualitative criteria highlight the need for assessments that are both comprehensive and context-sensitive, especially when heterogeneous dimensions are involved (Silva et al., 2024).

A critical issue highlighted in the literature is the gap between procurement practices and the multidimensional requirements of the decision. Initial evaluations based predominantly on financial considerations may in fact overlook ergonomics, safety, quality, and organizational aspects. Moreover, benefits and priorities depend on the sector and the type of work and are difficult to generalize as a universal rule. It follows that the decision should be structured as a task-based and scenario-based assessment, rather than as a standard choice to be replicated mechanically across different contexts (Thongdonnoi et al., 2023; Silva et al., 2024).

Finally, readiness and change management also include perceptual and relational dimensions. Evidence concerning fears of job loss, trust, and communication strategies indicates that these factors affect acceptance and the stability of implementation, while the literature points to the need for more applied studies in real-world contexts in order to understand long-term consolidation (Kopp et al., 2021). In SMEs, where roles and competencies are often concentrated, adoption may be more exposed to resistance and skills mismatches, with implications for operational continuity after installation.

5.1.3 Environmental Factors: Competitive Pressures, Institutional Support, and Regulatory Constraints

Within the environmental domain, cobot adoption is shaped by competitive pressures and by external resources and constraints that may accelerate or delay the decision, particularly in SMEs. Coercive, mimetic, and normative pressures related to customers, competitors, partners, and governments influence adoption. In addition, support from governmental institutions and research centers may facilitate access to

funding and pilot experimentation, acting as a bridge between public financing and firms (Correia Simões et al., 2020).

Alongside these drivers, the environment also includes regulatory constraints and external standards that enter the decision criteria in terms of compliance and safety. Frameworks integrating regulatory components and verifiable requirements support the need for multidimensional balancing and for systematic verification of constraints. Although these constraints originate outside the firm, they are operationally translated into internally verifiable requirements, such as documentation of the safety/work system and mitigation measures, thereby affecting design choices, implementation timeframes, and implementation costs (Salimbeni and Mamani, 2020).

5.1.4 Processual Lens: From TOE Factors to Their Transformation into Decisions and Stable Integration

The TOE framework clarifies which factors influence adoption, but translating them into a robust decision and stable integration requires a dynamic process of evaluation and adaptation. The uncertainty associated with technological novelty and evolution, the variability of performance outcomes in HRC configurations, and the role of acceptance and trust indicate that TOE determinants must be translated into coherent configuration choices and organizational changes (Correia Simões et al., 2020; Cohen et al., 2019; Silva et al., 2024; Kopp et al., 2021).

Within this framework, the chapter adopts a processual interpretation structured around three moments: the identification of opportunities and constraints, the selection of coherent configurations, and the translation of choices into actual changes in processes, roles, and routines. This interpretation is used as an interpretive guide to the decision-making process and not as an object of empirical testing of the theory. In the present work, this logic is operationalized in the model through the structuring of data collection, the adoption of implementability gates, the explicit formulation of assumptions, and the establishment of ex post monitoring.

5.1.5 Critical Synthesis and Gaps: Model Design Requirements

Overall, the literature converges in recognizing that cobot adoption is influenced by determinants attributable to the TOE framework and that successful integration

depends on the management of trade-offs and organizational adaptation (Correia Simões et al., 2020; Kopp et al., 2021; Silva et al., 2024). However, much of the available evidence is context-specific and difficult to generalize. Moreover, the asymmetry between easily calculable metrics and dimensions that are difficult to monetize may steer decisions toward partial assessments (Silva et al., 2022; Thongdonnoi et al., 2023).

Three main gaps emerge from this reading.

1. Gap between decision-making practices and socio-technical requirements. Decisions driven by immediate economic indicators may overlook organizational and human-centered factors that affect acceptance and stability; a model for SMEs must therefore integrate both “hard” and “soft” criteria (Thongdonnoi et al., 2023; Kopp et al., 2021).
2. Ambiguity of performance outcomes in HRC. Productivity in collaborative mode does not constitute an unambiguous advantage, since HRC constraints affect operating conditions; the model must therefore make trade-offs explicit and evaluate configurations from a task-based perspective (Silva et al., 2022; Silva et al., 2024).
3. Need for learning and monitoring. The decision should not be exhausted in the initial evaluation, but should include moments of verification and learning, especially in the presence of uncertainty and changes in the organizational and technical context (Kopp et al., 2021; Zemlyak et al., 2022).

The following measurable design requirements derive from these gaps: the model shall

- i. organize factors according to the TOE framework;
- ii. integrate multidimensional criteria while making trade-offs and uncertainties explicit;
- iii. treat the deployment configuration within the work system as the central choice;
- iv. adopt a processual logic consistent with the dynamic interpretation assumed;
- v. include a conceptual verification and a replicable validation plan.

TOE Domain	Factor (examples)	Decision Implication for SMEs	Criterion/Output in the Model	Planned Verification
Technology	Novelty/maturity, risk of obsolescence	Make uncertainty and timing explicit	Assumptions in TCO/ROI + sensitivity analysis	What-if analyses and scenarios
Technology	Task suitability, HRC constraints, safety-performance trade-off	Determine feasibility and realistic operational constraints	Technical gate + operating assumptions	Consistency of Gate → Scoring
Organization	Readiness, competencies, change management	Reduce hidden costs and implementation risk	Organizational gate + training plan	Completeness of the decision dossier
Organization	Acceptance, trust, communication	Reduce post-start-up instability	Governance checklist + training	Qualitative evidence in validation
Environment	Competitive pressures, external support	Consider funding, testing, and partners	Context data in the checklist	Traceability of external conditions
Environment	Regulatory constraints/standards	Integrate compliance and safety as a cross-cutting constraint	Safety/work system checklist + TCO items	Safety verification and impact on costs/time

Table 5.1: TOE mapping → decision implications → model criteria and planned verification.

Gap Identified in the Literature	Design Requirement	Model Component	Verification/Evidence
Decisions oriented toward immediate economic metrics	Integration of hard/soft criteria; traceability of assumptions	Checklist + decision dossier; organizational criteria in the scoring	Verification of decision dossier completeness
Performance ambiguity in HRC	Make HRC constraints explicit in the operating assumptions	Operating assumptions + criterion “impact of HRC constraints on throughput”	What-if analysis on HRC constraints
Gap between technology selection and socio-technical integration	Treat configuration as the object of the decision	Scenario-based alternatives; implementability gates; SOP	Consistency of Gate → Scoring
Uncertainty regarding useful life/obsolescence and timing	Make uncertainty explicit and test scenarios	Sensitivity analysis on useful life and costs	Scenarios in validation
Need for learning/monitoring	Introduce KPIs and ex post monitoring	Post-start-up KPIs; decision log	Reporting criteria

Table 5.2: Traceability of the contribution (gap → requirement → model component → verification/evidence).

In light of the mapping and the traceability of the contribution, the model developed in Section 5.2 adopts two central design choices:

- i. it treats the deployment configuration (namely HRC mode, task allocation, layout, and safety settings) as the explicit object of the decision;
- ii. it integrates the economic dimension (TCO, ROI, payback) with organizational and safety/work system criteria through gates and checklists, making assumptions, constraints, and trade-offs explicit.

5.2 Operational Decision-Making Model

This section proposes an integrated decision-making framework, structured into technical, economic, and organizational blocks and supported by an operational checklist, with the aim of increasing the transparency, traceability, and robustness of investment and configuration decisions regarding cobots in manufacturing SMEs.

The framework combines:

- technical criteria of feasibility and comparability, such as payload, reach, and minimum task quality prerequisites;
- economic criteria, with TCO as the cost structure and ROI and payback calculated on flows consistent with the operating assumptions;
- organizational and implementability criteria relating to readiness, training, and the safety/work system.

The process follows an operational sequence structured into six phases:

- i. collection of inputs and definition of the task baseline;
- ii. technical gate;
- iii. definition and comparison of configuration alternatives from a scenario-based perspective;
- iv. economic analysis (TCO + ROI/payback), integrated with sensitivity analysis;
- v. organizational and safety/work system gate;
- vi. multicriteria scoring among the admissible alternatives.

The checklist accompanies the process transversally and supports the preparation of the decision dossier, thereby reducing informational omissions and inconsistencies among technical, economic, and organizational estimates. The overall logic is

consistent with the most recent contributions highlighting the need for more comprehensive and better-supported decisions, capable of integrating quantitative and qualitative criteria and of being adapted to the company context (Silva et al., 2024).

The output consists of:

- a reasoned recommendation regarding the preferable alternative among the admissible ones;
- an explicit statement of the relevant trade-offs, particularly those associated with HRC constraints and their operational impacts;
- an action and responsibility plan in cases of conditional GO.

These outputs are incorporated into a decision dossier that includes at least: baseline and input data; formalized alternatives; gate outcomes and related justifications; operating assumptions, including in the form of intervals where appropriate; economic analysis (TCO, ROI, payback) and sensitivity analysis; scoring with weights and scores; and the decision log.

5.2.1 Logic and Decision Rule

The framework adopts a multicriteria logic aimed at balancing completeness and applicability in SME contexts. The deployment configuration is treated as the central design decision and is evaluated in a task-based and scenario-based manner. HRC constraints are made explicit in the operating assumptions and in the decision criteria. This choice is consistent with the literature emphasizing the need to integrate criteria that are difficult to monetize and to employ decision methods that are more comprehensive than economic analysis alone (Silva et al., 2022; Silva et al., 2024).

The decision-making process is structured into two stages:

- Gate (admissibility/implementability): application of non-compensatory minimum constraints;
- Scoring (selection among admissible alternatives): compensatory comparison among the alternatives that pass the gates.

Let a set of alternatives $j \in \{1, \dots, J\}$ and a set of scoring criteria $i \in \{1, \dots, I\}$ be considered. The weights w_i satisfy $\sum_{i=1}^I w_i = 1$, and the scores s_{ij} are defined on a 0-5 scale, with $s_{ij} \in [0, 5]$. The overall score of alternative j is given by:

$$Score_j = \sum_{i=1}^I w_i \cdot s_{ij}$$

In the case of equivalent or closely comparable scores, the decision gives priority to the alternative that exhibits greater stability with respect to the critical assumptions, namely the one yielding the most stable outcome in the sensitivity analyses; where stability is equal, preference is given to the lower TCO and, subsequently, to the shorter payback period. The rationale for the tie-break is recorded in the decision dossier.

- Gate (Admissibility/Implementability)

Each alternative is classified according to three possible outcomes: NO-GO, GO, and conditional GO.

- Technical gate: payload, reach, and minimum task quality prerequisites; compatibility with layout and space constraints.
- Organizational and safety/work system gate: availability of a preliminary RA prepared for the specific scenario, including identification of the main hazards, operating assumptions regarding zones, speeds, and separation distances, and candidate mitigation measures; minimum readiness, including roles, resources, and a training plan; governance, including a sponsor and a decision log.

In cases of conditional GO, the decision dossier must include mandatory actions, the responsible person, timeframes, estimated costs, and the closure criterion.

- Scoring (Selection Among Admissible Alternatives)

Among the alternatives that pass the gates, with an outcome of GO or conditional GO, selection takes place through multicriteria scoring on a 0-5 scale. The scoring also includes the residual operational impacts of HRC constraints on expected performance, such as speed limitations or procedural requirements, beyond the minimum compliance verified in the gates.

5.2.2 Scoring Rules and Score Construction (0-5 Scale)

To ensure comparability and replicability, each quantitative criterion, for example TCO, payback, and ROI, is converted into a score $s_{ij} \in [0, 5]$ through monotonic rules:

- for criteria to be minimized (TCO, payback), the better value, namely the lower one, corresponds to the highest score;
- for criteria to be maximized (ROI), the better value, namely the higher one, corresponds to the highest score.

The conversion rules, based on thresholds or normalization functions, and the reference intervals are documented in the decision dossier, so as to make score assignment traceable and different applications of the model comparable. For qualitative or semi-quantitative criteria, for example organizational effort, flexibility/reuse, and the impacts of HRC constraints on throughput, the 0-5 scale is defined through consistent descriptive anchors. The sensitivity of the ranking to scores and weights is verified through what-if analysis and sensitivity analysis.

- Mode A: Thresholds (Screening)

In SME contexts characterized by limited data availability, ex ante thresholds may be adopted to convert values into scores, provided that the rationale and the source of the selected thresholds are documented in the decision dossier.

- Mode B: Min-Max Normalization with Cap/Floor

When comparable values across alternatives are available, min-max normalization is adopted.

For criteria to be minimized (TCO, payback):

$$s_{ij} = 5 \cdot \frac{x_{max} - x_{ij}}{x_{max} - x_{min}}$$

For criteria to be maximized (ROI):

$$s_{ij} = 5 \cdot \frac{x_{ij} - x_{min}}{x_{max} - x_{min}}$$

with $x_{ij} \in [x_{i,min}, x_{i,max}]$. The decision dossier may include cap/floor values, controlled rounding, and the use of pessimistic, base, and optimistic intervals in order to avoid distortions due to anomalous estimates.

5.2.3 Technical Gate and HRC Operating Assumptions

The first block concerns technical parameters (payload, reach, and minimum task quality prerequisites) treated as admissibility constraints. The required quality is verified by comparing:

- the repeatability declared by the manufacturer, understood as a relative comparative indicator of the manipulator;
- the tolerances or quality criteria of the process.

In cases involving stringent requirements, this comparison is supplemented by pilot testing and/or precautionary margins. Since repeatability does not coincide with system accuracy, which also depends on EOAT, fixtures, calibration, and process conditions, the decision dossier must make these aspects explicit whenever they are decisive. If quality depends on absolute references or particularly stringent tolerances, the alternative is classified at least as conditional GO, with tests, fixtures, and calibration documented.

Collaborative constraints (zones, speeds, separation distances, and operating modes) are made explicit in the process assumptions and become inputs both for performance estimation and for the economic block, thereby influencing TCO and expected benefits.

Criterion	Metric/Unit	Data Source	Operating Rule (SMEs)	Outcome in the Model
Payload (primary)	kg	Task analysis + datasheet	Include EOAT; provide for a margin; avoid selections operating at the limit	Technical gate: GO/NO-GO
Reach (primary)	mm	Layout + datasheet	Verify coverage of positions and access points; consider actual space constraints	Technical gate: GO/NO-GO
Repeatability (primary)	mm	Datasheet + quality requirements	Task-based threshold; if close to the threshold or if system accuracy is critical → conditional GO with test/fixture/calibration	Technical gate: GO/conditional GO/NO-GO
HRC constraints (cross-cutting)	Zones/speeds/separation distances	Preliminary RA + layout	Make operational constraints explicit in the throughput assumptions	Input to the organizational/safety gate and to TCO
Secondary criteria (optional)	EOAT, vision, programming, flexibility, space	Suppliers + testing	Enter the scoring if discriminating	Scoring (0-5)

Table 5.3: Technical parameters as the technical gate and basis for comparability.

5.2.4 Economic Block and Assumptions on Cash Flows

Once technical feasibility has been established and the operating assumptions formalized, the framework incorporates an economic block to compare the alternatives in terms of financial sustainability and the temporal profile of benefits. In order to avoid distorted interpretations, the framework adopts TCO as the common cost structure:

$$TCO = CAPEX + \sum_{t=1}^N OPEX_t$$

where N represents the time horizon considered. ROI and payback are calculated on cash flows consistent with the operating assumptions and with the items included in the TCO; the monetization of “soft” benefits, such as ergonomics or risk reduction, is handled transparently and, where appropriate, complemented by qualitative assessments in the scoring. This approach is consistent with the literature, which highlights both the importance of costs and productivity in decision-making and the insufficiency of purely economic models when qualitative criteria or dimensions that are difficult to monetize come into play (Silva et al., 2024; Calvo and Gil, 2022).

Payback is calculated on the basis of cash flows. The annual net cash flow is considered, obtained as the difference between monetized benefits or estimated savings and incremental OPEX, and the first year in which the cumulative cash flow offsets CAPEX is identified, including integration and safety/work system costs. At the preliminary screening stage, when the data do not allow a reliable estimation of cash flows, a proxy may be used, for example the ratio between CAPEX and annual benefit, solely as an indicative measure, provided that it is made explicit in the decision dossier and accompanied by a sensitivity analysis of the underlying assumptions.

The economic analysis is completed by robustness checks through sensitivity analysis on critical variables, such as volumes, cycle times, useful life, labor cost, impacts of HRC constraints, and training, since sustainability may prove highly sensitive to these factors (Calvo and Gil, 2022; Cohen et al., 2019).

Dimension	Item/Indicator	Unit	Minimum Inputs	Robustness Note
CAPEX	Cobot purchase + EOAT	€	Quotations	Include necessary accessories
CAPEX	Integration (cell/PLC/interfacing)	€	Quotations + engineering hours	Item often underestimated
CAPEX/OPEX	Safety (measures + adaptations)	€	Preliminary RA → measures	Affects time and cost
OPEX	Maintenance and spare parts	€/year	Supplier data + estimates	Caution required with optimistic estimates
OPEX	Training and upskilling	€ / hours	Training plan	Influences implementation outcomes
Benefits	Time/cost, quality, ergonomics	€ / KPI	Baseline + estimate	Monetization only partial, where necessary
Summary	TCO + benefits	-	TCO + benefits	Depends on assumptions
Summary	ROI	%	Cash flow	Sensitive to volumes and productivity
Summary	Payback	months/years	Cash flow	Must be calculated on consistent cash flows
Robustness	Sensitivity	% variations	Volumes, times, useful life, labor cost, HRC/training	Recommended in every application

Table 5.4: Economic parameters: TCO structure, minimum inputs, and robustness checks.

5.2.5 Organizational and Safety/Work System Gate

A limitation of purely technical-economic models lies in implicitly assuming that the organization is ready to integrate and manage the cobot once it has been selected. The literature instead shows that the performance of the investment depends on competencies, managerial support, socio-technical configuration, and safety/compliance constraints. In the framework, these aspects are treated as actual implementability gates: an alternative is admissible only if minimum evidence of readiness exists and if a preliminary RA for the specific scenario is available, including the main risks, operating assumptions, and candidate mitigation measures, so as to make impacts on time and cost traceable as well (Kopp et al., 2021; Zemlyak et al., 2022; Salimbeni and Mamani, 2020).

Area	Minimum Indicator	Required Evidence	Outcome Rule (SMEs)
Training	Training plan (hours/roles) + contact person	Plan + schedule	GO / conditional GO / NO-GO
Readiness	Allocated resources (time, competencies, maintenance)	RACI / responsibilities	GO / conditional GO / NO-GO
Governance	Internal sponsor + decision log	Minutes / dossier	GO / NO-GO
Safety/work system	Preliminary RA for the scenario + candidate mitigation measures + layout	RA document + layout	GO / conditional GO / NO-GO
Acceptance (minimum)	Communication and management of impacts	Evidence of briefings/communications	GO / conditional GO / NO-GO

Table 5.5: Implementability gates: minimum organizational and safety/work system requirements.

5.2.6 Checklist and Decision Dossier

For SMEs, a framework is useful only if translated into repeatable and verifiable practices capable of reducing informational omissions and inconsistencies among technical, economic, and organizational estimates. The checklist standardizes minimum data and evidence, makes assumptions explicit, and supports governance through the assignment of responsibilities and the maintenance of the decision log.

Criterion	Scale	Weight (example)	Definition of 5	Definition of 0
TCO	0-5	0.20	Minimum TCO	Maximum TCO
Payback	0-5	0.15	Shortest	Longest / not recoverable
ROI	0-5	0.10	Highest	Lowest / negative
Robustness (sensitivity)	0-5	0.15	Stable ranking	Unstable ranking
Organizational effort/training	0-5	0.15	Minimum	Maximum
Impacts of HRC constraints on throughput	0-5	0.15	Limited impact	High impact
Flexibility/reuse	0-5	0.10	High	Low / lock-in

Table 5.6: Scoring among admissible alternatives (0-5 scale).

Macro-area	Item	Required Data	Responsible Party	Evidence	Status
Task & baseline	Task definition and volumes	Cycle times, mix, shifts	Production	Process sheet	☐
Task & baseline	Layout constraints	Spaces, positions, access points	Engineering/Maintenance	Layout	☐
Technical	Payload	Required kg + EOAT	Engineering	Calculation + datasheet	☐
Technical	Reach	mm + work envelope	Engineering	Layout + datasheet	☐
Technical	Repeatability	Required mm	Quality / Engineering	Quality requirements	☐
Configuration	Deployment alternatives	Comparable scenarios	Project team	List of alternatives	☐
Safety/work system	Preliminary RA (screening)	For selected scenarios	HSE / Engineering	RA + measures	☐
Economic	TCO	CAPEX/OPEX items	Finance / Engineering	TCO sheet	☐
Economic	ROI and payback	Time horizon and assumptions	Finance	Calculations + assumptions	☐
Robustness	Sensitivity	Critical variables	Finance / Engineering	Scenarios	☐
Organization	Training	Hours/roles/costs	HR / Production	Training plan	☐
Organization	Readiness	Resources/competencies	Management	RACI / resources	☐
Decision log	Rationale for the choice	Criteria and trade-offs	Project team	Minutes / dossier	☐
Monitoring	Post-start-up KPIs	KPIs + review timeframes	Production	KPI plan	☐

Table 5.7: SME operational checklist: concise template for the decision dossier.

5.2.7 User Guide to the Model (SOP): Inputs, Outputs, Roles, and Deliverables

To make the framework directly usable, an SOP is adopted specifying minimum inputs, the operational sequence, roles, and documentary deliverables.

1. Operational definitions (concise glossary)

- Baseline: current configuration of the task.
- Alternative: target scenario formalized in a comparable manner.
- Gate: sequential checkpoints with outcomes of NO-GO / GO / conditional GO.
- Scoring: integration of the evidence on a 0-5 scale according to explicit weights.

- Decision dossier: collection of evidence, assumptions, outcomes, and rationales.
- Post-start-up KPIs: indicators defined ex ante to verify consistency between expected benefits and achieved results.

2. Minimum inputs and information quality

Inputs are defined as “minimum” in the sense that they enable a robust comparative assessment without requiring full detailed design. The management of sources, plausible ranges, and assumptions is standardized in the decision dossier through the checklist, so as to ensure applicability and traceability.

The required minimum inputs are:

- task sheet and baseline (cycle times, volumes, mix, shifts, quality constraints);
- layout and space/access constraints, including the indication of dimensions and interfaces;
- configuration alternatives, consisting of the baseline and one or more HRC or light automation alternatives formalized as comparable scenarios;
- quotations and estimated costs (cobot, EOAT, integration, safety, maintenance, training);
- preliminary RA for each scenario, including the main risks, operating assumptions, and candidate mitigation measures.

3. Typical roles and responsibilities (light RACI)

Production and Quality validate the baseline and the requirements. Engineering and Maintenance formalize the alternatives and the integration constraints. HSE prepares the preliminary RA and defines constraints and mitigation measures. Finance structures the TCO and the economic indicators. Management approves the outcome on the basis of the decision dossier.

4. Operational steps (sequence and gates)

- i. definition of the scope (task, process boundaries, target KPIs, quality requirements);
- ii. collection of the baseline and completion of the checklist;
- iii. technical gate, with exclusion of unsuitable alternatives;
- iv. formalization of the alternatives according to a scenario-based logic (layout, task allocation, EOAT, HRC mode);
- v. economic analysis (TCO, ROI, payback based on cash flows);
- vi. sensitivity analysis on critical variables;
- vii. organizational and safety/work system gate, with outcome of GO/conditional GO/NO-GO and definition of any action plan required;
- viii. scoring and decision, including ranking and rationale;
- ix. final output: recommended choice and post-start-up KPI plan.

5. Scoring Weights (Permissible Operational Modes)

To reduce arbitrariness and increase transparency, the framework allows three weighting modes, all of which must be documented in the decision dossier:

- uniform weights as a baseline, $w_i = 1/I$, accompanied by sensitivity analysis;
- workshop with internal stakeholders (Production, Quality, HSE, Engineering, Finance), with consensual assignment and formal recording in the minutes;
- “light” AHP or simplified pairwise comparisons.

In all cases, the minimum requirement is that weights be explicit, justifiable, and subjected to sensitivity analysis.

6. Outputs

The outputs of the framework include:

- The complete decision dossier, with the checklist and technical, economic, and safety attachments;
- the alternative matrix with the gate outcomes;

- the TCO sheet and ROI/payback calculations based on cash flows, accompanied by sensitivity analysis;
- the scoring table with weights, scores, and rationale;
- the decision log and the post-start-up KPI plan.

5.2.8 Minimal Illustrative Example (End-to-End, Fictitious Data)

To illustrate the functioning of the framework without resorting to a real case, a micro-example based on fictitious data is proposed, constructed so as to retrace the entire logical chain of the model, from the definition of the baseline to the final recommendation.

1. Definition of the Task and Baseline

Consider a screwdriving task with a manual baseline of 40 s/piece, an annual volume of 50,000 pieces, and a time horizon of $N = 5$ anni. Three alternatives are considered:

- A: manual baseline, used as the reference;
- B: HRC configuration in coexistence, in which collaborative constraints affect the expected benefits;
- C: separated cell, with potentially greater benefits but higher CAPEX.

2. Technical Gate

It is assumed that alternatives B and C are suitable with respect to payload, reach, and repeatability; both therefore obtain a technical GO outcome. Baseline A does not require an admissibility assessment, since it represents the reference state.

3. Formalization of the Operating Assumptions

For alternative B, it is assumed that collaboration in coexistence requires speed limitations and operating procedures that affect effective throughput. For alternative C, by contrast, a separated cell is assumed, with safety measures that are more readily standardizable, but with greater initial integration complexity.

4. Economic Analysis Based on Cash Flows (Fictitious Data)

- CAPEX: $B = 55 \text{ k€}$; $C = 75 \text{ k€}$.
- Annual OPEX: $B = 5 \text{ k€}$; $C = 6 \text{ k€}$.
- Estimated annual gross benefit: $B = 25 \text{ k€}$; $C = 30 \text{ k€}$.
- Annual net cash flow (gross benefit - OPEX):

$$B = 20 \text{ k€}/\text{year}$$

$$C = 24 \text{ k€}/\text{year}$$

From these assumptions, the following are obtained:

- Payback (continuous approximation):

$$B \approx 55/20 = 2,75 \text{ year}$$

$$C \approx 75/24 = 3,13 \text{ year}$$

- TCO over 5 years:

$$B \approx 55 + 5 \cdot 5 = 80 \text{ k€}$$

$$C \approx 75 + 6 \cdot 5 = 105 \text{ k€}$$

5. Minimum Sensitivity Analysis on the Assumptions

Two sensitivity scenarios are considered.

- S1: annual volume -20%. Benefits decrease by 20%; the net cash flow becomes:

$$B = 16 \text{ k€}/\text{year};$$

$$C = 19,2 \text{ k€}/\text{year}$$

In this scenario, payback worsens for both alternatives.

- S2: HRC penalty on alternative B. It is assumed that collaborative constraints reduce the gross benefit of alternative B by 30%. The new net cash flow of B becomes:

$$(25 \cdot 0,7 - 5) = 12,5 \text{ k€}/\text{year}$$

and the corresponding payback is:

$$55/12,5 = 4,4 \text{ year}$$

In this case, the ranking may become unstable, showing the relevance of the assumptions concerning HRC constraints.

6. Organizational and Safety/Work System Gate

- B: conditional GO outcome, since it requires specific training, operational mitigation measures, and verification of the HRC assumptions.
- C: GO outcome, since the measures are more readily standardizable, albeit with greater initial integration effort.

For alternative B, the decision dossier must therefore include corrective actions, responsibilities, timeframes, estimated costs, and the closure criterion for the conditional GO.

7. Scoring and Final Decision

The scoring integrates TCO, payback, ROI, and non-economic criteria, such as ranking stability, organizational effort, impacts of HRC constraints on throughput, and flexibility, using explicit weights. Where the scores are closely comparable, the tie-break rule gives priority to the alternative that is more stable with respect to the critical assumptions; where parity remains, TCO and payback are then considered.

The micro-example is intended solely for illustrative purposes, but it shows comprehensively how the framework makes explicit:

- i. the transition from inputs to alternatives;
- ii. the selective function of the gates;
- iii. the effect of operating assumptions on economic results;
- iv. the role of sensitivity in the stability of the ranking;
- v. the production of a reasoned recommendation that can be documented in the decision dossier.

5.3 Model Verification in the Absence of an Application Case: Quality, Consistency, and Conceptual Robustness

In the absence of an application case, model verification is framed as a conceptual verification of the decision-making framework. The aim is not to measure the model's effectiveness empirically, but rather to demonstrate that it is executable, unambiguous, and internally consistent. The rules must therefore be replicable, and the output, understood as the final recommendation, must be reconstructible from the inputs and the intermediate decisions.

Consistent with the methodological positioning adopted, conceptual verification serves here a specific function: to show that the model possesses a sufficient level of maturity to be regarded as complete from a design perspective, even in the absence of field validation. This implies that the quality of the chapter is assessed on the basis of properties such as the traceability of the rules, the consistency between decision-making steps, the explicit management of assumptions, and the framework's ability to produce outcomes that are interpretable and documentable.

The verification focuses on three fundamental properties:

- traceability of the decision-making process, in the sequence input → checklist → gate → scoring → recommendation;
- informational completeness of the dossier, with respect to the minimum inputs required to apply the rules;
- conceptual robustness of the outcome, with respect to plausible variations in the critical assumptions.

Four main criteria are adopted:

- traceability: the possibility of reconstructing the decision-making path through the decision log;
- consistency: the absence of contradictions between gate constraints and the final outcome; NO-GO excludes the alternative, whereas conditional GO requires verifiable conditions;
- robustness: interpretable stability of the ranking as assumptions and weights vary;
- implementability: compatibility of the alternative with the safety/work system and organizational constraints; if not fully satisfied, the alternative may result only in conditional GO, with an action plan and closure criteria.

This approach is consistent with the literature emphasizing the importance of safety, acceptance, appropriate configuration, organizational support, and the need for more applied forms of verification beyond the laboratory setting alone (Kopp et al., 2021; Silva et al., 2024).

To make the conceptual verification unambiguous, the following operational tests are adopted.

1. Gate → Scoring Test (Non-compensability)
 - Rule: any alternative with at least one NO-GO outcome does not proceed to the scoring stage.
 - Required evidence: gate outcome and rationale recorded in the decision dossier.
2. Conditional GO Test (Verifiable Closure)
 - Rule: a conditional GO alternative proceeds to the scoring stage only if the dossier contains activities, responsibilities, timeframes, costs, and the criterion for closure of the condition.
 - Required evidence: action plan attached to the decision log.
3. Informational Completeness Test (Checklist-Based)
 - Rule: if a critical input is missing, such that it affects the gates or the main drivers of the scoring, the alternative is handled either through a prudential assumption made explicit and justified, or through a conditional GO outcome accompanied by data-collection activities.
 - Required evidence: completed checklist and assumptions log, including ranges and rationale.
4. Tie-Break Consistency Test
 - Rule: the tie-break rule (stability → TCO → payback) is applicable only among admissible alternatives; the rationale must be recorded.
 - Required evidence: entry in the decision log referring to the sensitivity results.
5. Robustness is explored through:
 - what-if analysis on technical and economic assumptions (demand, cycle times, integration costs, impacts of HRC constraints, labor cost);
 - sensitivity analysis on the scoring weights, verifying that reasonable variations produce interpretable changes and do not violate the logic of the gates.

For the purposes of conceptual verification, a mini-sensitivity analysis is presented on two weighting schemes, consistent with Table 5.6, applied to alternatives B and C in the micro-example. The following scores on a 0-5 scale are assumed, consistently with the outcomes illustrated:

- B: TCO = 5; Payback = 4; ROI = 4; Robustness = 2; Organizational effort = 3; Impacts of HRC constraints on throughput = 2; Flexibility = 4
- C: TCO = 3; Payback = 3; ROI = 3; Robustness = 4; Organizational effort = 2; Impacts of HRC constraints on throughput = 4; Flexibility = 3

1. Scheme P1 (baseline, consistent with Table 5.6):

TCO 0.20; payback 0.15; ROI 0.10; robustness 0.15; organizational effort 0.15; HRC impacts 0.15; flexibility 0.10.

Result:

- Score B = 3.45
- Score C = 3.15

Under this scheme, alternative B ranks first.

2. Scheme P2 (oriented toward implementability and operational performance):

TCO 0.15; payback 0.10; ROI 0.05; robustness 0.25; organizational effort 0.15; HRC impacts 0.20; flexibility 0.10.

Result:

- Score B = 3.05
- Score C = 3.30

Under this second scheme, alternative C ranks first.

The outcome is interpretable: as greater weight is assigned to robustness and to the impacts of HRC constraints on throughput, preference shifts toward the alternative that is more stable and less operationally penalized by collaborative constraints. Where scores are closely comparable, the tie-break rule gives priority to the more stable alternative, thereby maintaining consistency with the general logic of the framework.

The mini-sensitivity analysis does not constitute empirical evidence, but it strengthens the demonstration of the executability and internal consistency of the decision rule. Overall, the conceptual verification shows that the framework is executable, traceable, and coherent in its interdependencies, and that the output

remains interpretable with respect to plausible variations in assumptions and preferences.

5.4 Replicable Empirical Validation Plan (for Future Work)

The empirical validation of the framework is intended to verify that it supports reproducible, traceable, and implementable decisions in real production contexts, generating comparable evidence on its discriminatory capacity among alternatives, on the robustness of the ranking with respect to data, assumptions, and weights, and on its implementability within the work system. Validation therefore strengthens the external validity of the framework and assesses its transferability across tasks and contexts.

Replicability is pursued through standardized deliverables:

- input dossier, including the completed checklist, sources, and level of confidence;
- formalized description of the alternatives;
- simulation protocol and/or field evidence collection protocol;
- set of KPIs with operational definitions;
- KPI → economics mapping, integrated with TCO, ROI, and payback;
- results of sensitivity analyses, both on parameters and on weights;
- evidence of implementability and readiness (safety/work system, competencies, procedures);
- summary of lessons learned and conditions of applicability.

The plan is structured into four steps:

1. collection and verification of inputs;
2. formalization of realistic alternatives;
3. application of gates and scoring with a decision log;
4. validation through simulation and/or case study with sensitivity analysis.

This structure is consistent with contributions emphasizing the relevance of simulation, comparison among alternatives, operational KPIs, and the integration of economic and performance-based decision-making, while not exhausting all the organizational dimensions of the problem (Thongdonnoi et al., 2023; Calvo and Gil, 2022; Silva et al., 2024).

5.4.1 Validation through Simulation: Requirements and KPIs

Simulation is appropriate when experimentation on the actual system is costly or risky. In the proposed plan, simulation is used to generate comparable KPIs and to inform the economic assumptions (TCO, ROI, payback) transparently, including robustness checks.

The unit of analysis is the task, or a family of homogeneous tasks. The alternatives considered must be at least two, and preferably three or four, including the baseline and differentiated HRC configurations. Boundaries and operating policies must be made explicit.

When the task is embedded within a broader cell or production line, system-level KPIs are included only if necessary to represent interdependency effects that cannot be captured at the level of the single task.

The KPIs are divided into:

- core KPIs, always present: throughput/equivalent cycle time, resource utilization, bottlenecks, labor requirement;
- system-level KPIs, where applicable to the scope: average WIP, waiting times, lead time, output variability.

The KPIs must have operational definitions consistent across alternatives and must inform both the scoring and the KPI → economics mapping. The focus on throughput, waiting times, WIP, bottlenecks, and labor requirements is consistent with the findings of studies using simulation to compare cobot deployment alternatives in manufacturing contexts (Thongdonnoi et al., 2023).

5.4.2 Validation through Case Study: Implementability and Threats to Validity

The case study is essential for validating the organizational and socio-technical component, by verifying that the checklist, gates, and scoring can be completed and reproduced using realistic evidence in an SME, and that the recommended alternative is effectively implementable within the work system (Kopp et al., 2021; Zemlyak et al., 2022).

The main threats to validity concern the quality and granularity of the data, the representation of HRC constraints, the accuracy of integration and safety estimates, and the transferability of the results. The corresponding mitigation measures include

triangulation of sources, construction of alternative scenarios, sensitivity analysis, formal declaration of assumptions and confidence level, as well as full traceability in the decision log.

5.4.3 Synthesis of the Design and Reporting Criteria (Triangulation of Evidence)

The plan combines simulation and case study in order to triangulate evidence on discriminatory capacity, robustness, and implementability. Reporting should include:

- alternatives and assumptions;
- KPIs and their operational definitions;
- KPI → economics mapping;
- gate outcomes with rationales;
- scoring with weights, scores, and tie-break rules;
- results of the sensitivity analyses;
- evidence of implementability and lessons learned.

5.5 Chapter Closure: Synthesis and Link to the Conclusions

This chapter has shown that cobot adoption and the likelihood of their stable integration in manufacturing SMEs depend on technological, organizational, and environmental determinants attributable to the TOE framework, as well as on the firm's ability to translate these determinants into deployment configurations consistent with the work system and with safety/work system constraints (Correia Simões et al., 2020; Kopp et al., 2021; Silva et al., 2024). The critical synthesis of the literature highlighted three recurring gaps-namely, the gap between decision-making practices and socio-technical requirements, the ambiguity of performance outcomes in HRC configurations, and the need for learning and monitoring-which justify the adoption of an integrated decision-making approach tailored to the SME context (Thongdonnoi et al., 2023; Zemlyak et al., 2022; Silva et al., 2024).

Section 5.2 proposed an operational decision-making model (Gate + Scoring), integrated with a checklist and an SOP, with an explicit statement of its scope, assumptions, limitations, and an end-to-end illustrative example. Section 5.3 defined the conceptual verification of the model, centered on criteria of quality, internal consistency, dossier completeness, and what-if/sensitivity analysis, including

operational tests and a mini-sensitivity analysis on the weights to support the internal soundness of the framework. Section 5.4 formalized a replicable empirical validation plan, based on simulation and/or case study, to be developed in future work with the aim of strengthening external validity and transferability across tasks and contexts.

The absence of an empirical application delimits the scope of the contribution, but does not diminish its conclusive character at the design level. The contribution of the thesis lies, in fact, in the design, formalization, and conceptual verification of a complete decision-making model, usable as a structured decision-support and preliminary screening tool. In this sense, the chapter does not present a preliminary or incomplete result, but rather an outcome consistent with the declared scope of the work: a decisionally usable framework, methodologically positioned, and prepared for subsequent empirical validation.

The assessment in real-world contexts, necessary to estimate its performance, stability, and transferability, is deferred to the validation phase outlined in Section 5.4. The thesis conclusions will critically discuss the contribution and limitations of the model, further clarify the relationship between conceptual verification and empirical validation, and define a roadmap for the application and calibration of the framework, including verification of the conditions for applicability and transferability across tasks and production contexts.

CONCLUSION AND FUTURE DEVELOPMENTS

This thesis has examined the impact of collaborative robots on productivity and work organization in manufacturing SMEs, adopting a perspective that jointly considers technical, economic, and organizational aspects. Within this framework, attention was not focused solely on the technology itself, but on the socio-technical system into which the cobot is introduced: cell configuration, safety constraints and human-robot collaboration, skills, and operating practices. This multidimensional complexity makes it necessary to adopt a tool capable of supporting SMEs in comparing alternatives in a coherent and documentable manner; for this reason, the work culminates in the proposal of a structured decision-making model (understood as both a procedure and a tool to support decision-making) that accompanies the transition from the adoption phase (assessment of the opportunity and selection of the solution) to the integration phase (implementation, stabilization, and governance within the work system).

The analysis developed in this thesis highlights that the impact of cobots on productivity can be significant, but it is not automatic: it depends on the correct selection of the task, the design of the cell, and the balance between operational performance, safety constraints, and production variability. In this thesis, productivity is understood primarily as the improvement of process performance (cycle times/throughput and resource utilization) and economic sustainability, assessed on the basis of realistic demand scenarios and production configurations. From an organizational perspective, the integration of cobots entails a reconfiguration of work toward supervisory tasks, exception handling, and quality control. This requires adequate skills and an explicit approach to organizational change management and operator involvement. Consequently, the adoption decision proves more robust when it integrates technical, economic, and organizational dimensions within a single structured assessment; the proposed decision-making

model aims to make this process clear, justifiable, and consistent with the typical operating conditions of SMEs.

Summary of the Main Results

Chapter 1 - From Traditional industrial robotics to cobots: evolution, principles, and adoption drivers. The evolutionary framework leading from traditional industrial robotics to collaborative robotics was defined, highlighting how cobots address needs that are typical of SMEs: flexibility, reconfigurability, and greater operational accessibility. The distinction between adoption (investment decision and selection of the solution) and integration (implementation, stabilization, and governance of the technology within the work system) was also clarified, emphasizing that the benefits depend on the alignment between the technical solution and work organization.

Chapter 2 - Medium-Payload Cobots in SMEs: Classification of Applications, Productivity KPIs, and Integration Challenges. A systematic interpretation of the main cobot applications in manufacturing contexts was proposed, with particular attention to the tasks most readily transferable within SMEs (for example, machine tending and repetitive handling operations) and to the prerequisites for integration (layout, tooling, operational interfaces, and safety). The chapter highlighted the importance of relating each application to comparable scenarios and measurable indicators, distinguishing between local performance KPIs (cycle times, utilization, bottlenecks) and system-level KPIs (lead times and flow variability), in order to avoid partial or non-comparable evaluations.

Chapter 3 - From manual operator to operator-supervisor: the impact of cobots on skills, safety, and well-being. The introduction of cobots was interpreted as a process of reconfiguring work and roles. In particular, the operator tends to evolve from the executor of repetitive manual activities into a role more strongly oriented toward supervision, control, exception handling, and quality. This gives rise to implications for training, technical-operational skills, and awareness of safety constraints, as well as for factors related to acceptance and human-robot collaboration. From this perspective, the effectiveness of integration also depends on the organization's ability to define procedures, responsibilities, and practices consistent with the new allocation of tasks.

Chapter 4 - Economic Evaluation of the Adoption of Collaborative Robots in Manufacturing SMEs. An economic evaluation framework for collaborative robotics projects was defined, distinguishing the main cost components and adopting a life cycle-oriented perspective. It emerged that, in SME contexts, economic viability is particularly sensitive to operational variables such as actual annual hours, utilization, production mix, and reconfiguration times; therefore, it is essential to make scenario assumptions explicit and, wherever possible, to integrate credible proxies for benefits related to quality, scrap, and rework. When available, such proxies feed into the decision dossier and strengthen the comparison among alternatives.

Chapter 5 - Decision-Making Model for the Adoption and Integration of Cobots in Manufacturing SMEs. On the basis of the evidence that emerged, a decision-making model was proposed to guide the process from task selection to the choice of the integration alternative and the definition of the monitoring plan. The model combines a preliminary phase for verifying implementability (technical, organizational, and safety-related) with a multicriteria assessment that integrates economic sustainability, operational impacts, flexibility, and organizational requirements. The adopted logic makes assumptions and trade-offs explicit and supports comparison among scenarios. In the present work, the model was defined and verified in terms of coherence and conceptual applicability; empirical validation through simulation and/or a case study is instead formalized as a future development.

Original Contribution of the Thesis

The original contribution of this work can be summarized in three main elements:

1. Integration of dimensions that are often treated separately: the thesis proposes a unified framework that connects technical aspects (task and cell), economic aspects (costs, benefits, and indicators), and organizational aspects (roles, skills, and operating practices), framing cobot adoption as a socio-technical decision.
2. Proposal of an operational decision-making model for SMEs: the model makes it possible to move from problem description to the justified selection of a solution, combining implementability checks with explicit multicriteria

criteria, together with documentation of the assumptions and evidence supporting the decision.

3. Centrality of scenarios and decision robustness: the approach emphasizes the construction of realistic scenarios and the explicit formulation of operational and economic assumptions, reducing the risk of overestimation and making the assessment more closely aligned with the variability typical of SME contexts.

Practical Implications for SMEs

From an applied perspective, this work provides a useful reference for guiding collaborative automation choices in a more structured manner and in a way that is less dependent on exclusively technological evaluations. In particular, the proposed decision-making model can support SMEs in:

- identifying and prioritizing candidate tasks, translating them into comparable integration scenarios;
- defining technical and organizational requirements before the investment, by establishing procedures, skills, and safety conditions consistent with human-robot collaboration;
- assessing economic sustainability on the basis of explicit assumptions consistent with the context (volumes, utilization, shifts, reconfigurations), thereby avoiding overly optimistic or poorly transferable interpretations;
- establishing post-start-up verification criteria, by defining KPIs and review timelines in order to consolidate integration and foster organizational learning.

In decision-making terms, this work supports the company in defining a structured path: assessing the opportunity for investment (go/no-go), selecting and prioritizing candidate processes, choosing the integration configuration most consistent with constraints and objectives, and defining criteria and KPIs for verifying post-start-up results.

Limitations of the Work

The limitations of this thesis are consistent with the objective of proposing a decision-making model applicable to SMEs and with the typical constraints of the industrial contexts analyzed. The main limitation concerns the absence of empirical validation of the decision-making model: the artifact was designed and structured in an operational manner, and its internal coherence and conceptual applicability were verified, but it was not tested through simulation or an industrial case study. Consequently, the effectiveness of the model in real contexts and its transferability across companies with different characteristics require experimental verification.

A second limitation concerns the availability and quality of data in many SMEs, where some critical variables (for example, actual times, micro-stoppages, and systematic quality indicators) may be measured in an incomplete or non-standardized way. In such cases, the evaluation must be based on estimates, proxies, and plausible ranges; this does not invalidate the proposed framework, but it reinforces the need to make assumptions explicit and to assess the sensitivity of the results with respect to the most influential variables.

Finally, the thesis adopts an application scope oriented toward transferability: the discussion prioritizes applications and indicators that are typical and more widespread in manufacturing SMEs, with a focus on pick-and-place and machine tending, and on medium-payload cobots. More complex solutions, or those that depend heavily on advanced digital infrastructures, would require extensions of the model as well as more stringent organizational and technological prerequisites.

Future Developments

Future developments can be articulated along three main directions.

1. Empirical validation through case studies and/or simulation. The application of the decision-making model in one or more real manufacturing SME contexts is a priority, in order to verify its ability to guide robust decisions in the presence of actual constraints (variability, safety, and plant conditions). Alternatively, or in parallel, validation through scenario simulation would make it possible to compare different configurations and systematically test the impact of variability and operational disruptions on performance and

economic viability. In terms of outputs, the validation could measure the stability of the ranking among alternatives as scenarios vary, as well as the consistency between estimated KPIs and observed or simulated KPIs.

2. Collection of industrial data, parameter calibration, and sensitivity analysis. A further development consists in building a minimum set of industrial data to improve the reliability of the inputs and calibrate the economic and operational parameters (times, availability, scrap, reconfigurations, utilization). This would make it possible to strengthen the estimation of costs and benefits over the life cycle and to formalize a structured sensitivity analysis, identifying break-even thresholds for different configurations of volumes, shifts, and production mix.
3. Extensions of the model. The model can be expanded by introducing new KPIs (for example, more granular quality measures, more structured ergonomic indicators, reliability, and post-start-up stability), adaptations to different sectors and tasks, and a more explicit assessment of risks and digital maturity (data and traceability). From this perspective, the organizational readiness already considered in the model could be quantified and detailed through more specific criteria, making the evaluation more accurate even in contexts with different levels of technical-organizational complexity.

In conclusion, the thesis highlights that the integration of cobots in SMEs cannot be interpreted as a simple technological choice: it is a socio-technical decision that requires consistency among production objectives, safety constraints, economic sustainability, and work design. The proposed decision-making model helps connect technical-economic analysis and organizational implications, offering SMEs an operational reference for deciding whether, where, and how to introduce collaborative robotics in a sustainable manner. From this perspective, empirical validation and calibration on industrial data represent the natural continuation of the work, transforming the model into a fully verified and transferable tool for integration decisions in SMEs.

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