D3.1 – Robots composition data description

WP3 - Task 3.1

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An Artificial Intelligence (AI) driven Agent was used to search and collect any information concerning the topic. It then generated based on this extensive web search a comprehensive with data listing. All essential information is directly referenced to the used sources of the internet search. This allows to verify all important aspects of the basic investigation. DeepAgent from Abacus.ai was used for this purpose. The AI tool Claude Opus was used to generate all the Python code used for data consolidation. The authors retain full accountability for the content and its accuracy.

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Summary

The dataset presented in this document is a part of Deliverable 3.1. and provides information on the consolidated material composition dataset for different types of robots.

Keywords

Robots, Single arm robots, Industrial transport robots, Humanoid robots

Abbreviations and acronyms

Acronym	Description
AI	Artificial Intelligence
WP	Work Package

1 Introduction

This dataset provides consolidated information on the component and material composition of different types and use-cases of robots. Robots are composed of a structural frame and a set of functional subsystems - most importantly actuators and transmissions, sensors, control electronics, power supply, and (where applicable) onboard computing - whose configuration and relative importance vary with the robot's primary task. For example, industrial robots (single-arm manipulators) are typically dominated by high-precision joints, geared drives, and rigid link structures to achieve accuracy and repeatability, whereas industrial transport robots (e.g., mobile platforms) place greater emphasis on the drive train, energy storage, safety sensors, and navigation hardware. Humanoid robots combine both locomotion and manipulation, resulting in higher overall subsystem diversity and often a greater number of actuated degrees of freedom, which can substantially increase material intensity.

Beyond functional differences, robot composition is also shaped by factors such as size and payload class, kinematic architecture (arm geometry, wheeled vs. legged locomotion), duty cycle, and safety and reliability requirements. Design choices related to actuation technology (electric, hydraulic, or hybrid), structural materials, battery capacity and thermal management, and sensor/computing integration lead to distinct material demands and environmental footprints across robot types. Understanding these compositional differences is therefore essential for assessing resource use, lifecycle impacts, and expected trends in robot deployment and design, especially as automation expands from controlled industrial settings to more general-purpose and human-facing environments.

2 Product structure and component definition

This section provides a detailed analysis of the product architecture and component definitions, following a structured approach that breaks down the physical composition of robots into their fundamental subsystems. To reflect the significant differences in design and functional requirements across the field, the analysis is split into three subchapters dedicated to the primary robot categories: industrial robots (single-arm manipulators), industrial transport robots, and humanoid robots. As illustrated in Figure 1, these categories are further structured through a hierarchical product key system, where each main robot type (productKey1) is subdivided into specific families (productKey2), capturing variations in size, capability, and application domain.

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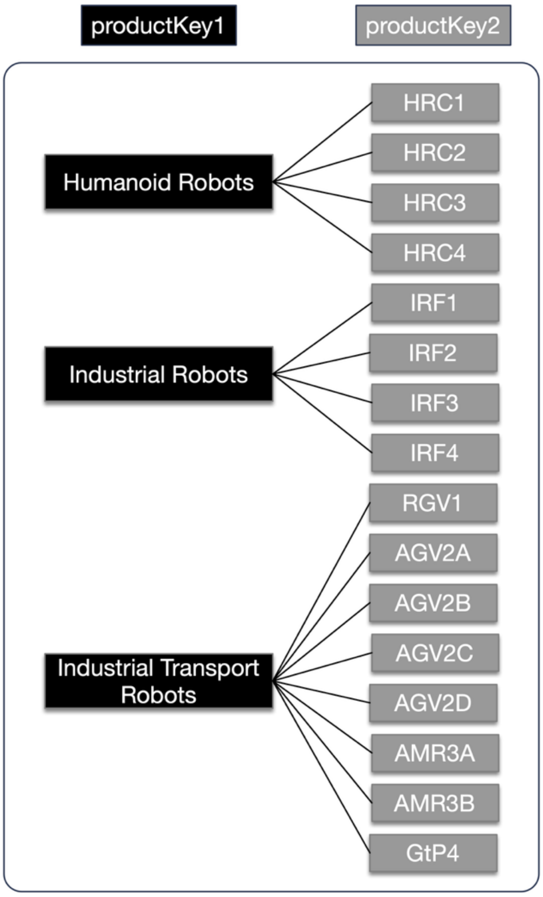

Figure 1: Hierarchical structure of robot classification, mapping primary robot categories to their respective family subtypes.

Each subchapter defines the specific architectural layout of the respective robot type, identifies the key functional components—including structural frames, actuation systems (motors and gearboxes), sensors, electronics, and power units—and describes how these elements are integrated to fulfill the robot's operational purpose. The product key structure shown in Figure 1 provides the basis for linking these functional definitions to representative configurations, ensuring that differences between robot types and families are consistently captured. This standardized decomposition enables a coherent comparison of material intensity and component complexity across the different robot classes.

2.1 Industrial Robots (one arm robots)

The product structure and component definition for industrial robots follow a hierarchical decomposition that organizes the system into functional subsystems and their constituent parts. This architecture is defined through two primary levels: componentKey0, representing major assemblies, and componentKey1, identifying specific mechanical and electronic elements. As illustrated in Figure 2, this systemic approach ensures that the diverse range of industrial robot families - from small SCARA units to heavy-payload articulated arms - can be parameterized using a consistent and comparable inventory of functional blocks.

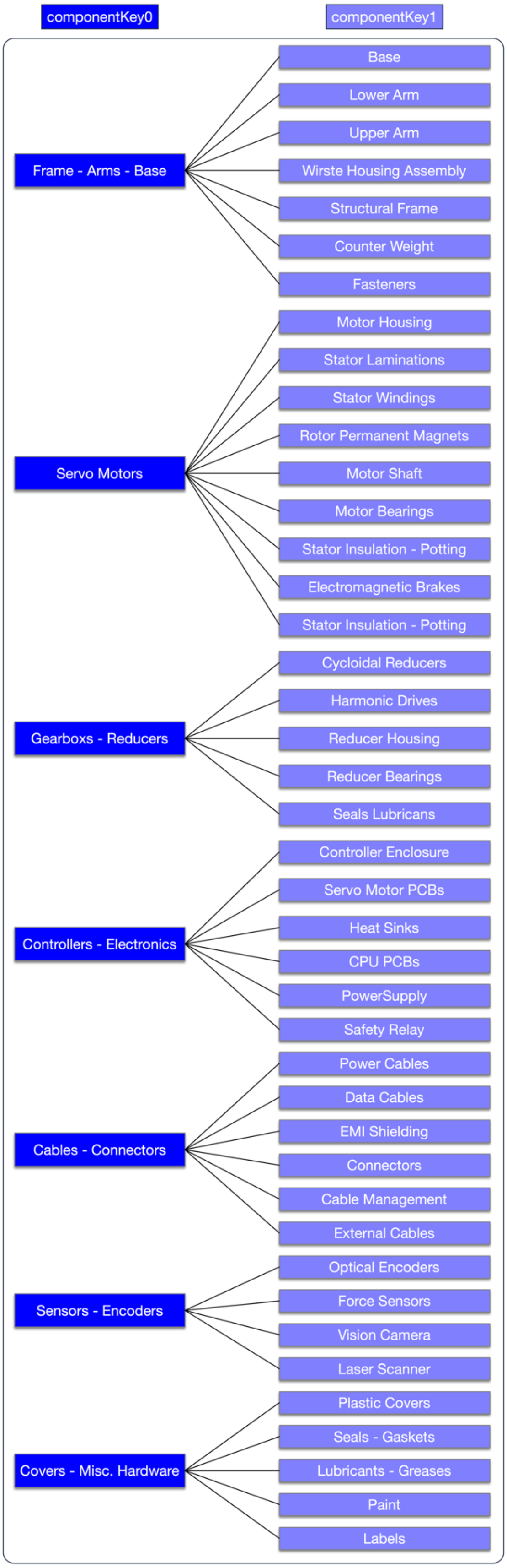

Figure 2: Hierarchical mapping of robot product categories to specific family sub-types and their associated material composition profiles.

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At the primary level (componentKey0), the industrial robot is divided into seven core subsystems. The structural backbone is formed by the Frame, Arms, and Base, which provides the necessary rigidity and geometry for manipulation. Motion is generated and controlled through the Servo Motors and Gearboxes/Reducers subsystems, which together translate electrical energy into high-torque, precision movement. The Controllers and Electronics subsystem serves as the central intelligence, managing power distribution and trajectory execution, while the Cables and Connectors and Sensors and Encoders subsystems provide the essential signal and power pathways and real-time positional feedback required for closed-loop control. Finally, Covers and Miscellaneous Hardware account for protective elements, seals, and finishing materials.

Each subsystem is further detailed at the componentKey1 level to capture the full mechanical and material complexity of the robot. For example, the structural subsystem includes specific links such as the Base, Lower Arm, Upper Arm, and Wrist Housing, as well as Counterweights used in larger models. The actuation and drive-train sections are particularly detailed, specifying elements like Stator Laminations, Windings, and Permanent Magnets within the motors, and Cycloidal Reducers or Harmonic Drives within the gearboxes. Similarly, the electronics and sensing sections breakdown into PCBs, Heat Sinks, Optical Encoders, and Laser Scanners. This granular definition allows the model to accurately account for the differing material intensities of each functional unit, providing a rigorous basis for subsequent mass and material composition analysis.

2.2 Humanoid Robots

The product structure of humanoid robots is defined through a classification into four main robot classes, which capture distinct differences in weight, capability, and primary application domains. These classes range from high-performance industrial systems to accessible educational platforms, covering the full spectrum of current humanoid development. Industrial workhorses represent full-size systems, typically in the 70–73 kg range, designed for robust deployment in structured environments like manufacturing or logistics with high payload capacities and significant degrees of freedom (DOF). In contrast, dynamic research platforms vary more widely in weight and emphasize extreme mobility and agility - such as running or jumping - often utilizing high-power actuation systems optimized for research rather than immediate commercial runtime.

The classification further distinguishes between human-facing and academic systems. Service and interaction robots are generally light-to-medium weight (30–60 kg) and are optimized for safe navigation and emotional feedback in public or domestic spaces, prioritizing natural language processing and human-robot interaction over raw power. Finally, lightweight and educational platforms provide a more affordable entry point for academic research and STEM education, featuring moderate capabilities and open-source frameworks. This productKey structure allows the dataset to link each class to representative configurations while accounting for varying regulatory and safety standards, such as ISO 13482 for personal care or EU AI Act requirements for high-risk interaction.

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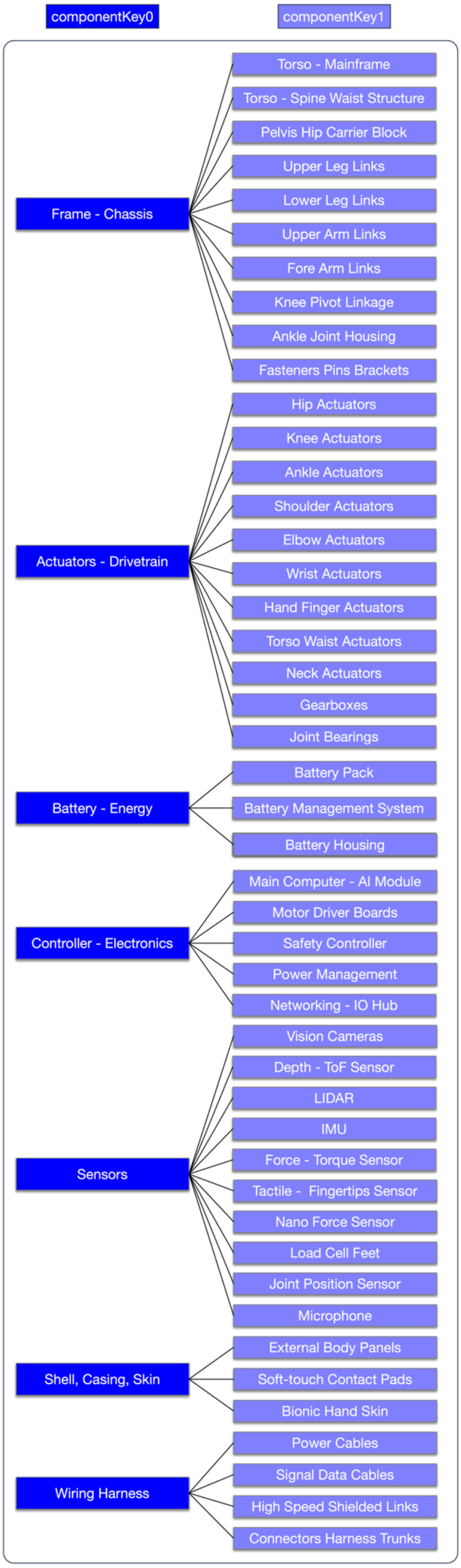

Figure 3: Hierarchical decomposition of humanoid robot architecture, mapping primary functional subsystems to specific structural, electronic, and mechanical components.

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As shown in Figure 3, this product classification is directly linked to a detailed component-level hierarchy. At the primary level (componentKey0), the humanoid is decomposed into its essential physical subsystems: the frame and chassis (the structural skeleton), the actuators and drivetrain (the muscles and joints), the battery and energy system, controllers, sensors, the outer shell, and the wiring harness. Each of these is further refined into specific elements (componentKey1), such as torso mainframes, limb links, specialized sensors like LiDAR or IMUs, and intricate bionic skins. This hierarchical mapping ensures that the significant functional complexity of humanoid robots - particularly their high number of actuated joints and dense sensor arrays - is systematically translated into a detailed representation of component composition and material requirements.

2.3 Industrial Transport Robots

The product structure of industrial transport robots is defined through a classification based on payload capacity, navigation principle, and operational environment. The dataset distinguishes several main classes, including rail-guided vehicles (RGVs), different categories of automated guided vehicles (AGVs), autonomous mobile robots (AMRs), and fixed-infrastructure goods-to-person systems. These classes span a wide range of payloads - from lightweight systems handling a few tens of kilograms to heavy-duty transport platforms exceeding several tens of tonnes - and reflect fundamentally different deployment concepts. For example, RGVs operate on fixed rail systems with extremely high precision and uptime, while AGVs follow predefined paths using magnetic, optical, or laser guidance, and AMRs enable flexible navigation through sensor-based localization and dynamic path planning.

Within this classification, the dataset further refines the productKey structure by distinguishing subcategories according to functional use and performance range. AGVs are divided into tugger/truck systems (2A), platform and unit-load carriers (2B), pallet stackers (2C), and forklift-type systems (2D), each corresponding to different logistics tasks such as towing, lifting, or high-bay storage. Similarly, autonomous mobile robots are split into lower and upper performance ranges, reflecting differences in payload, system size, and complexity. In addition, fixed infrastructure systems such as AS/RS and cube storage solutions represent a distinct class where movement is constrained to predefined grids or aisles and coordinated centrally. This structured classification captures both technological diversity and operational constraints, while aligning with relevant standards such as ISO 3691-4, VDA 5050, and EN safety regulations, which govern safety, navigation, and system integration.

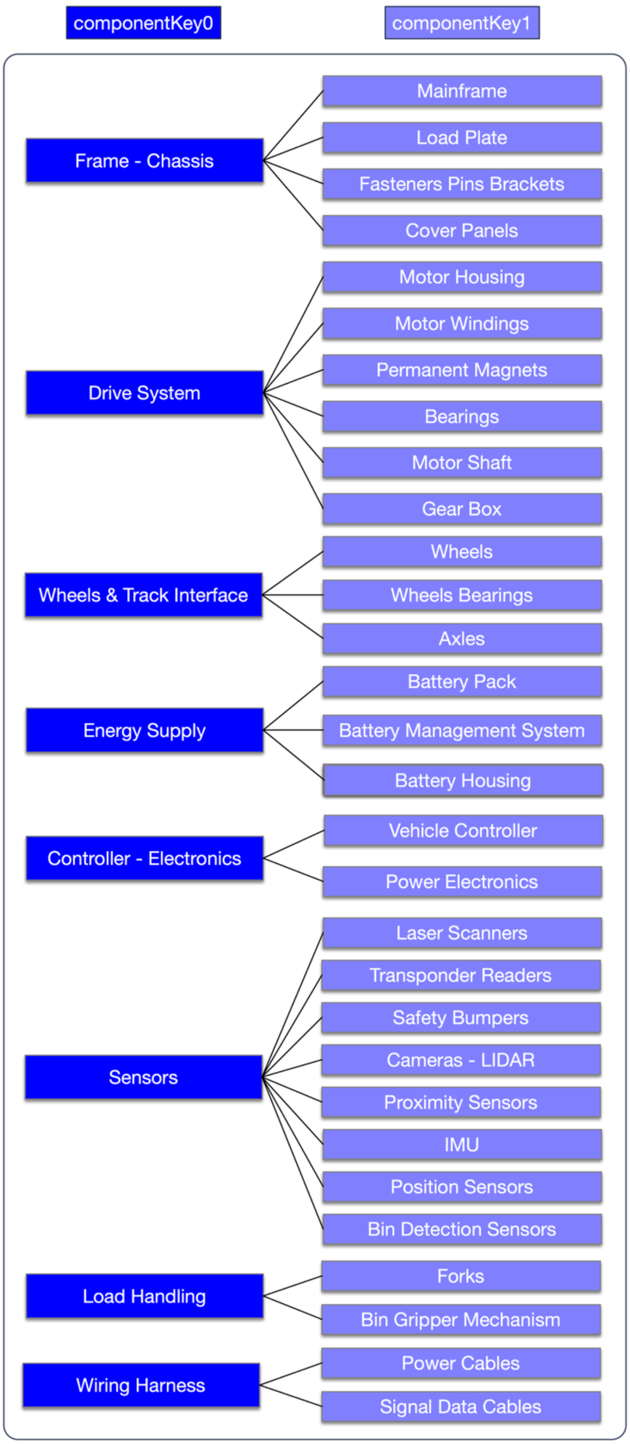

Figure 4: Hierarchical decomposition of industrial transport robot architecture, illustrating the relationship between core functional subsystems and their specific mechanical, electronic, and load-handling components.

Based on this product classification, the component structure of industrial transport robots is defined through a hierarchical decomposition into major subsystems, as illustrated in Figure 4. At the primary level (componentKey0), the system is divided into core functional groups: frame and chassis, drive system, wheels and track interface, energy supply, controller and electronics, sensors, load handling systems, and wiring harness. These subsystems reflect the essential physical and functional building blocks required for mobility, control, and interaction with the environment. At the next level (componentKey1), each subsystem is further specified

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into detailed elements such as motor housings, gearboxes, wheels and axles, battery systems, power electronics, laser scanners, proximity sensors, and load-handling mechanisms such as forks or grippers. This hierarchical approach ensures that differences in robot class—such as fixed-track versus fully autonomous systems—are consistently translated into differences in component composition and, ultimately, material requirements.

3 Specifications and modelling principles

This chapter describes the specification and modelling principles applied to represent the different robot systems in a consistent and quantitative manner. Building on the previously defined product and component structures, it explains how each product category - industrial robots, industrial transport robots, and humanoid robots - is parameterized using the productKey classification. The objective is to translate heterogeneous real-world systems into a standardized set of variables that can be directly used in modelling approaches such as life cycle assessment (LCA), stock-and-flow analysis, or resource demand projections. In this context, the product keys define representative system configurations, while the associated component and material data provide the basis for quantifying mass, composition, and scaling behavior.

A central element of the modelling approach is the use of minimum (min), most likely (mode), and maximum (max) values to describe key parameters such as system mass, component quantities, or functional shares. This allows the model to capture both typical configurations and the variability observed across real-world systems. Depending on the application, these values can be used deterministically (e.g., using the mode as a representative case) or probabilistically (e.g., sampling within the defined range to reflect uncertainty). The following three subchapters describe in detail how this approach is applied to each main product category (productKey1), including the assumptions, parameter ranges, and aggregation logic used to derive consistent and comparable modelling inputs.

3.1 Industrial Robots (one arm robots)

The specification of one-arm industrial robots at the productKey2 level is based on a structured family approach that groups robots into a limited number of representative categories reflecting their size, performance, and application domain. Starting from the kinematic architecture (e.g., articulated, SCARA, delta, or Cartesian), each robot is assigned to one of five families (IRF-1, IRF-2A, IRF-2B, IRF-3A, IRF-3B). These families capture the progression from small, high-speed precision robots to large, heavy-payload systems, and are characterized by key technical parameters such as total system weight, payload capacity, reach, and number of axes or motors. The accompanying summary table provides typical ranges for these parameters, allowing each family to serve as a representative proxy for a broader set of real-world robot models.

FamilyID	**Description**	**Typical Total Weight** (kg)	**Payload** (kg)	**Reach** (mm)	**Axis/Motors**
IRF-1	Small Precision	15 – 60	up to 12	up to 1100	3 - 6
IRF-2A	Lower Medium	150 – 825	12 – 156	1400 – 2200	6
IRF-2B	Upper Medium	825 – 1500	156 – 300	2200 – 3000	6
IRF-3A	Lower Heavy	1700 – 6350	300 – 1300	2400 – 3200	3 - 6
IRF-3B	Upper Heavy	6350 - 11000	1300 - 2300	3200 - 4000	3 -6

A key modelling refinement is the subdivision of the original medium and heavy robot categories into lower-range and upper-range subfamilies. This is achieved using a consistent transformation of the original min, mode, and max values, where the lower-range families (IRF-2A, IRF-3A) span from the original minimum to the original mode, and the upper-range families (IRF-2B, IRF-3B) span from the original mode to the original maximum. In both cases, a new mode value is introduced as the midpoint of the respective interval. This approach preserves the original variability while increasing resolution within the most relevant performance ranges, enabling a more accurate representation of the diversity of industrial robots without introducing discontinuities.

Within the modelling framework, each family serves as a parameterized archetype that links product characteristics to component composition and material use. Once a robot is assigned to a family, the corresponding parameter ranges are used to estimate subsystem masses and material distributions based on the component definitions described earlier. The use of min/mode/max values allows flexibility in application: the mode can be used for deterministic modelling, while the full range supports probabilistic analyses and uncertainty propagation. This structured specification ensures that industrial robots of varying sizes and capabilities can be consistently integrated into broader modelling approaches such as LCA or stock-and-flow analysis.

3.2 Humanoid Robots

The specification of humanoid robots at the productKey2 level is based on a classification into four distinct robot classes, which reflect differences in system weight, functional capabilities, and primary application domains. These classes - Industrial Workhorse (HRC1), Dynamic Research Platform (HRC2), Service & Interaction Robot (HRC3), and Lightweight & Educational Platform (HRC4) - provide representative categories that capture the current diversity of humanoid systems. Each class is characterized by key parameters such as weight range, degrees of freedom (DOF), payload capacity, runtime, and intended use case, as summarized in the accompanying table. For example, industrial workhorses are full-size systems (around 70 - 80 kg) optimized for robust and repetitive industrial tasks, whereas lightweight platforms can be as small as 5 kg and are primarily designed for education and prototyping.

Robot Class	Weight Range (kg)	Primary Use Case
1 Industrial Workhorse	70 - 80	Operational deployment in structured industrial environments: manufacturing, logistics, warehousing
2 Dynamic Research Platform	45 - 90	R&D exploration of locomotion, agility, and dynamic control; not immediate commercial deployment
3 Service & Interaction Robot	30 - 60	Direct interaction with people: hospitality, retail, healthcare, education, entertainment
4 Lightweight & Educational Platform	5 - 55	Academic research, STEM education, hobbyist development, prototyping

In contrast to industrial robots, where families are derived from continuous scaling of payload and size, humanoid robot classes are defined more strongly by functional orientation and interaction context. Dynamic research platforms prioritize mobility and advanced control (e.g., running or jumping), often at the expense of operational runtime, while service robots emphasize human–robot interaction (HRI) capabilities such as perception, communication,

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and safe operation in unstructured environments. These distinctions are reflected not only in performance metrics but also in system design choices, including actuator technology, sensor density, and computational requirements. As a result, each class represents a distinct configuration of subsystems rather than a simple scaling of a common architecture.

Within the modelling framework, each humanoid robot class serves as a parameterized archetype that links system-level characteristics to component composition and material requirements. The specified ranges for weight, payload, and functional capabilities define the boundary conditions for estimating subsystem masses and component distributions. While explicit min/mode/max values are less directly derived than in the industrial robot case, the defined ranges can be interpreted analogously to support both representative (mode-like) and scenario-based (range-based) modelling. This ensures that humanoid robots—despite their high variability and evolving design paradigms—can be consistently integrated into quantitative analyses such as LCA or stock-and-flow modelling.

3.3 Industrial Transport Robots

The specification of industrial transport robots at the productKey2 level is based on a functional classification that reflects differences in payload capacity, navigation technology, and logistics application. The dataset distinguishes several robot classes, including rail-guided vehicles (RGVs), multiple categories of automated guided vehicles (AGVs), autonomous mobile robots (AMRs), and fixed-infrastructure goods-to-person systems. Each class is defined by key parameters such as payload range, operational capabilities, and navigation method, as summarized in the accompanying table. For example, RGVs represent very heavy systems with payloads up to 200,000 kg and extremely high positioning accuracy, while AMRs operate in a much lower payload range but provide high flexibility through autonomous navigation and dynamic obstacle avoidance.

In contrast to industrial and humanoid robots, where classification is largely driven by mechanical structure or functional capabilities, industrial transport robots are primarily differentiated by their logistics role and level of autonomy. The AGV category is further subdivided into tugger systems (2A), platform or unit-load carriers (2B), pallet stackers (2C), and forklift systems (2D), each representing distinct material handling tasks such as towing, lifting, or high-bay storage operations. In addition, autonomous mobile robots are separated into lower and upper performance ranges, reflecting differences in payload, system complexity, and sensor requirements. Fixed-infrastructure systems such as AS/RS or cube storage solutions form a separate class, where movement is constrained to predefined rails or grids and coordinated by centralized control systems. This classification is closely aligned with established standards such as ISO 3691-4 and VDA 5050, ensuring consistency with industrial practice and safety requirements.

Robot Class	Payload Range (kg)	Key Capabilities
1 Rail-Guided Vehicle (RGV)	5 000 – 200 000	Extreme payload transport; ±0.3 mm positioning accuracy; 99.8 % uptime; lifting & rotary functions; flush-floor track
2A Tugger / Tractor AGV	1 000 – 20 000	Tow multiple non-motorised carts (milk-run); auto-coupling/decoupling; line-side replenishment
2B Platform & Unit-Load AGV	50 – 130 000	Carry loads on flat top surface; lift mechanism for carts/racks; conveyor-top integration
2C Pallet Jack & Stacker AGV	900 – 3 000	Floor-to-floor pallet transport; stacker lifts to ≤4.75 m; auto pallet detection

2D Forklift AGV	1 500 – 10 000	Counterbalance / reach / VNA; lift to ≤12 m; high-bay storage & retrieval; precise load handling
3 Autonomous Mobile Robot (AMR)	100 – 1 500	SLAM autonomous navigation; dynamic obstacle avoidance; fleet management; rapid deployment; no infrastructure mods
4 Fixed-Infra Goods-to-Person (AS/RS & Cube)	30 – 3 175 (bin/pallet)	Cube-storage (AutoStore); shuttle AS/RS; crane AS/RS; up to 85 % floor-space saving; goods-to-person picking

Within the modelling framework, each robot class serves as a parameterized archetype linking system-level characteristics to component composition and material demand. The defined payload ranges and functional capabilities provide the basis for estimating subsystem sizes, drive system requirements, energy storage capacity, and sensor configurations. Similar to the other robot categories, the modelling approach allows the use of range-based specifications (analogous to min/mode/max) to capture variability across real-world systems, while still enabling the definition of representative configurations for deterministic analyses. This ensures that industrial transport robots - with their wide diversity in scale, infrastructure dependency, and autonomy - can be consistently integrated into applications such as LCA, fleet modelling, or stock-and-flow analysis.

4 Conclusion

In conclusion, the hierarchical modelling framework established across these robotics categories provides a robust, quantitative bridge between high-level functional profiles and granular material compositions. By utilizing a multi-level productKey system - whether based on industrial robot families, transport payload bands, or humanoid research classes - the model successfully translates the immense diversity of the global automation landscape into standardized, parameterized archetypes. This structured approach allows researchers and analysts to navigate the inherent complexity of these systems while maintaining a consistent accounting of physical components, from the structural frames and high-performance actuators of a humanoid robot to the specialized drive systems and sensor arrays of industrial transport and manipulation units.

Furthermore, the implementation of uncertainty modelling through minimum, mode, and maximum values ensures that the resulting data remains both representative of typical configurations and reflective of real-world variability. This flexibility is essential for the reliable application of the dataset in life cycle assessments (LCA), resource demand projections, and stock-and-flow analyses, where understanding the range of possible material impacts is as critical as identifying the central tendency. Overall, this standardized methodology provides a scalable and transparent foundation for assessing the long-term resource intensity and environmental footprint of the rapidly advancing automation technologies that are redefining modern industrial and service environments.

5 Contributors

- Matthias Rösslein – Data collection, data model and consolidation, all coding
- Rebeka Anspach – Review
- Bíborka Boga – Review
- Harald Desing – Review

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- Lukas Feldmann – Review
- Kirsten Remmen – Coordination, PI

6 Raw data references

An extensive list of reference for the data sources are given in the attached report:

- final_one_arm_industrial_robot_report_extended_subsystems.pdf
- humanoid_robot_materials_and_components_report.pdf
- industrial_transport_robots_final_report.pdf

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