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Towards Humanoid Robot Implementation in Construction

Identifying Technical, Informational, Process and Organizational Requirements for On-Site Integration

Master's thesis in Design and Construction Project Management

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Abstract

Although recent advances in robotics have increased interest in construction automation, the implementation of advanced robotic systems remains challenging. Construction environments are highly dynamic and primarily designed for human workers, while BIM-based information structures are generally developed for human interpretation rather than machine execution. Consequently, a gap exists between the operational requirements of advanced robotic systems and current construction practices.

The study explores how construction environments, BIM systems and organizational structures must evolve to support robotic execution. Through a theoretical and analytical approach combining literature on robotics, BIM and construction management with expert interviews and a case-based perspective from a construction company, the study translates humanoid robotic capabilities into construction-specific system requirements.

The findings show that advanced robotic implementation requires machine-readable and semantically structured BIM data, standardized workflows, predictable site conditions and increased organizational coordination. The study also identifies significant gaps between current construction practices and the requirements of autonomous robotic systems, particularly regarding information management, process standardization and alignment between digital models and physical environments.

The thesis concludes that enabling humanoid robots in construction requires not only technological development, but also broader transformation of construction systems, workflows and governance structures. The findings contribute to a broader understanding of the systemic changes required for increased automation in the construction industry.

Keywords: humanoid robots, construction automation, Building Information Modeling (BIM), on-site construction, construction processes

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Tilda Cronsell and Alice Westberg, Gothenburg, May 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AI	Artificial Intelligence
BIM	Building Information Modeling
HRC	Human-Robot Collaboration
IMU	Inertial Measurement Unit
LiDAR	Light Detection And Ranging
SLAM	Simultaneous Localization And Mapping

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1
Introduction

The construction industry is currently facing several challenges such as low productivity, labor shortages and health and safety risks (Belousov et al., 2022; Kim et al., 2021). Compared to manufacturing and other industrial sectors, construction has historically shown limited levels of automation and digital integration despite increasing project complexity (Kromoser & Reichenbach, 2021). These inefficiencies have increased the search for new technological approaches capable of transforming on-site production (McKinsey Global Institute, 2017).

Research and industry initiatives have explored robotics, digital fabrication and artificial intelligence (AI) as potential ways to achieve more industrialized construction processes (Eastman et al., 2018). Although automation has significantly increased in prefabrication and factory-based environments, the construction industry on-site is not part of this development to the same extent (Külz et al., 2025). Previous studies show that robotics can improve productivity, precision and worker safety, particularly in repetitive or dangerous tasks (Khan et al., 2025; Kim et al., 2021; Li et al., 2025). However, most construction robots used to date have been task-specific systems operating in controlled conditions, which limits their applicability in broader construction environments (Bock, 2015). While research increasingly demonstrates the technical potential of robotic systems, less attention has been given to how these capabilities can be translated into practical construction requirements. Existing studies primarily focus on robotic technologies, BIM applications or individual automation solutions in isolation. Consequently, there is limited understanding of how construction sites, BIM models, workflows and organizational structures must evolve to support the implementation of advanced robotic systems. As a result, a gap remains between the capabilities demonstrated in research and the realities of current construction practice.

Recent advances in humanoid robotics have renewed interest in automation within traditional construction environments (Odugu et al., 2025; Uthai et al., 2026). Unlike specialized robotic systems, humanoid robots are designed to operate in spaces and with tools that were originally intended for human workers. This characteristic makes them particularly relevant for on-site building production where environments are unstructured, variable and designed for human ergonomics. A recent framework for humanoid robots in construction highlights their potential to perform tasks such as material handling, drilling, assembly, inspection and collaborative operations, while also identifying significant technical and organizational barriers to implementation (Uthai et al., 2026).

Despite technological advances in robotics, the integration of humanoid systems into construction workflows presents fundamental challenges beyond hardware development. Construction sites are dynamic environments characterized by frequent layout changes, incomplete information and deviations between design and built conditions. Effective robotic implementation therefore requires reliable digital representations of both planned and actual site conditions (Wang et al., 2024). This highlights the need for digital information systems that can structure, manage and communicate such information in a consistent and machine-readable way. Without such systems, advanced robotic technologies cannot be effectively integrated into construction workflows.

Building Information Modeling (BIM) has been identified as an important enabler for automation in the construction industry. BIM provides structured digital representations of geometry, semantics and scheduling information which create a potential interface between design and robotic execution (Kim et al., 2021; Wong Chong et al., 2022). However, current BIM practices are primarily developed for human interpretation, coordination and documentation rather than machine execution. This misalignment between design models and production requirements remains a significant barrier to automation (Wong Chong et al., 2022). Studies have shown that robotic systems require highly structured, precise and machine-readable information to perform tasks accurately (Kim & Peavy, 2022; Wilkins & Kiviniemi, 2008; Wong Chong et al., 2022).

This thesis addresses this transformation by examining the requirements necessary to enable humanoid robots in on-site building construction, focusing on how BIM and construction processes must evolve to support robotic execution. As humanoid robots represent an advanced stage of automation, this analysis also provides insights into the broader conditions required for increasing automation in construction.

1.1 Problem Formulation

Although existing research demonstrates the technical capabilities of robotic systems and highlights BIM as a potential enabler for construction automation (Kim et al., 2021; Odugu et al., 2025; Wang et al., 2024), limited attention has been given to the broader construction system required to support their implementation. In particular, there is a lack of research examining how robotic capabilities translate into practical requirements on BIM, construction processes, site conditions and organizational structures. Consequently, the relationship between what humanoid robots are capable of doing and what the construction industry must provide to enable their effective use remains insufficiently understood.

This indicates a gap between technological development and implementation readiness. Previous studies have identified several barriers to construction automation, including fragmented processes, limited standardization and challenges related to digital information management (Tafazzoli et al., 2024). However, how these barriers relate specifically to the implementation of humanoid robots remains largely unexplored. Addressing this gap is important because the successful adoption of humanoid robots depends not only on advances in robotics, but also on the ability of construction projects to provide the information, processes and organizational conditions required for robotic operation. There is therefore a need to investigate how BIM, construction processes and organizational structures must evolve to support the implementation of humanoid robots in construction projects.

1.2 Aim and Objectives

The aim of this thesis is to identify and analyze the physical, informational and organizational requirements necessary to enable humanoid robots in on-site building production by translating robotic capabilities into construction system requirements. In addition, the study investigates how the processes, structures and competencies of a construction management company must evolve to support such implementation.

To achieve this aim, research is structured around a set of specific objectives:

- Identify and translate humanoid robot capabilities into requirements for construction systems.

- Propose standardized and production-adapted modeling approaches that support automation while maintaining cross-disciplinary flexibility.

- Evaluate the potential benefits of using humanoid robots to automate construction tasks on-site.

- Explore how a construction management company can adapt its processes to support humanoid robot implementation.

Although the study primarily focuses on humanoid robots, the analysis is intended to contribute to a broader understanding of how construction systems must evolve to support increasing levels of automation.

1.3 Research Questions

Main research question:
What requirements must construction sites, BIM models and organizational processes fulfill to enable the integration of humanoid robots in on-site construction?

Sub-questions:
- What technical capabilities do humanoid robots require to operate on construction sites?

- What types of information and modeling structures must be incorporated into BIM models to enable their use in robotic construction processes?
- How must current construction workflows adapt to enable the integration of humanoid robots?
- How must organizational structures, competencies and responsibilities evolve within a construction company to enable humanoid robot adoption?

1.4 Scope and Delimitations

This master's thesis investigates the requirements necessary to enable the future implementation of humanoid robots in on-site building construction. The study focuses specifically on identifying physical, informational and organizational requirements related to construction sites, BIM and organizational processes. The analysis considers indoor construction environments, where conditions are comparatively more controlled than on outdoor construction sites.

The scope is limited to on-site construction environments rather than off-site or factory-based production, as humanoid robots are particularly relevant in environments originally designed for human workers. From a project management perspective, such environments involve complex coordination, dynamic workflows and multi-actor interactions, which are central aspects of construction projects.

The study further emphasizes BIM as a digital interface between design and execution, with a particular focus on its potential role in supporting robotic construction. However, the thesis does not aim to develop new BIM software tools or implement technical integration solutions.

The research adopts a theoretical and analytical approach. It examines humanoid robot capabilities described in existing research and industry reports, and translates these into construction-specific requirements. The study does not involve the development, programming or testing of robotic systems, and no experimental validation, algorithm development or technical prototyping is conducted.

A case application involving a construction company is included to illustrate how current processes and BIM practices relate to the identified requirements. However, the study does not evaluate financial feasibility, return on investment or detailed contractual implementation strategies. Broader economic market analyses are therefore outside the scope of this thesis.

Finally, the thesis does not assess the ethical implications of artificial intelligence in depth, nor does it include a comprehensive legal review. Legal and regulatory aspects are only discussed to the extent that they influence the feasibility of humanoid robot implementation in construction.

1.5 Thesis Outline

This thesis is structured into seven main chapters and their content is outlined below.

Chapter 1 introduces the research background, problem formulation, aim, research questions and scope of the study.

Chapter 2 presents the framework of reference. It examines previous research on humanoid robotics in construction, BIM as a digital interface for automation and process transformation in the construction industry.

Chapter 3 describes the research design, including analytical approach, data collection and design of the case application.

Chapter 4 presents the empirical findings of the study. It identifies physical, informational, processual and organizational requirements necessary to enable humanoid robots in on-site construction.

Chapter 5 applies the identified requirements to a selected case project in order to evaluate how construction processes and BIM practices must evolve to support robotic integration.

Chapter 6 discusses the implications of the empirical findings in relation to existing literature and empirical results. It reflects on how the results contribute to the current understanding of humanoid robot integration in construction and highlights key challenges and limitations.

Chapter 7 concludes the thesis by summarizing the key findings and providing direct answers to the research questions. It emphasizes the overall contributions of the study and includes a final reflection on its implications, along with suggestions for future research.

2

Framework of Reference

This chapter presents the framework of reference used to examine how humanoid robots could be enabled in on-site building construction. The chapter progressively builds from robotic capabilities to construction requirements, forming the basis for the analytical framework used in the study.

2.1 Robotics in Construction

The use of robots in the construction industry is increasing and is often motivated by challenges related to productivity, safety and labor availability (Bock, 2015; Uthai et al., 2026). However, the application of robotics in construction is still relatively limited and mainly focused on well-defined and repetitive tasks where automation can provide clear benefits (Bock, 2015). This is largely due to the complex and dynamic nature of construction environments, which makes full automation difficult to achieve (Oesterreich & Teuteberg, 2016; Tafazzoli et al., 2024). Today's robotic systems are typically designed to perform specific tasks within predefined boundaries (Bock, 2015). They consist of both the physical robot and the supporting control mechanisms required for operation (Siciliano et al., 2010). Most systems are semi-automated and rely on human support for setup, calibration and supervision, particularly when site conditions change (Bock, 2015). As a result, robots currently function as tools that support human labor rather than fully autonomous systems (Uthai et al., 2026).

Examples of current robotic applications in the construction industry include 3D printing, bricklaying, drilling and layout marking. In these cases, robots perform repetitive or well-defined operations based on planned instructions. These systems can improve efficiency and precision, but are typically limited in their ability to adapt to changing site conditions and therefore require controlled environments or human supervision (Casini, 2022). Beyond current robot applications, there are more advanced applications, including robots used for tasks requiring higher levels of accuracy and interaction with building components, such as assembly or wall-finishing (Bock, 2015). These systems are often more closely integrated with digital construction processes, where digital models provide information about geometry, locations and construction sequences (Casini, 2022; Odugu et al., 2025). This provides a stronger connection between design and execution, although the systems still operate within relatively constrained conditions (Bock, 2015).

2.1.1 Humanoid Robots in Construction

A new generation of robots designed to operate in environments built for humans has been developed in recent years. These are called humanoid robots and are considered a potential response to challenges such as labor shortages, hazardous working conditions and low productivity (Uthai et al., 2026). Unlike traditional industrial robots, which are often stationary and designed for single, repetitive tasks, humanoid robots have a human-like body structure with arms and legs, which allows them to operate in environments designed for human ergonomics. Construction sites are inherently structured around human movement and tools, where workers navigate uneven surfaces, carry materials and use handheld equipment. Due to their physical configuration, humanoid robots may operate in such environments without requiring major changes to site design (Siciliano et al., 2010; Uthai et al., 2026). In addition, they are equipped with advanced sensors and perception systems that enable them to interpret their surroundings and adapt to changing conditions, in contrast to earlier construction robots that typically followed fixed and preprogrammed paths (Uthai et al., 2026).

Several humanoid robot platforms are currently being developed by technology companies and research institutions. Some examples are shown in Figure 2.1, including Honda ASIMO, Boston Dynamics Atlas, Tesla Optimus, Agility Robotics Digit and Apptronik Appollo (Uthai et al., 2026). Most of these systems are not specifically designed for construction, but they demonstrate capabilities such as dynamic locomotion and mobile manipulation that may be relevant for future on-site applications.

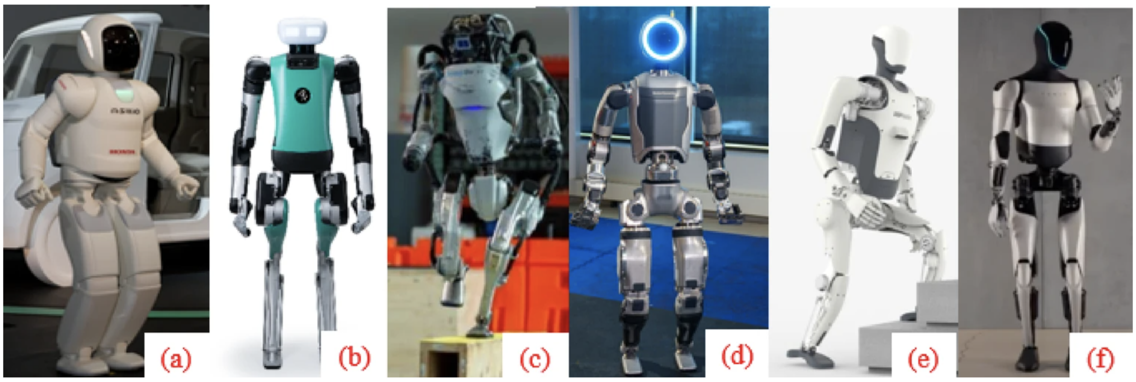

Figure 2.1: Humanoid robots have gained increasing attention in recent years. The examples shown include: (a) ASIMO from Honda; (b) Digit from Agility Robotics; (c–d) Atlas HD and the new Atlas from Boston Dynamics; (e) DR01; and (f) Optimus from Tesla. Reprinted from Uthai et al. (2026), under CC BY-NC-ND 4.0.

Despite technological advances, the cost of humanoid robots remains a significant barrier to wide adoption. While exact prices are often not publicly disclosed, available estimates suggest that current systems can range from approximately 100,000 to over 500,000 US dollars per unit depending on functionality and level of autonomy, with ongoing development aiming to significantly reduce costs in the future (International Federation of Robotics, 2024; KeyiRobot, 2025; Uthai et al., 2026). Tesla is currently working on a humanoid robot called "Tesla Optimus" and they are estimated to cost between 20,000 to 30,000 US dollars per unit (Teknik, 2025).

2.1.2 Comparison with Other Industries

Other industries, such as manufacturing, have achieved high levels of automation compared to the construction industry (Bock, 2015; McKinsey Global Institute, 2017). Manufacturing environments are typically standardized, repetitive and controlled which makes it easier to implement robots and automated systems, as it allows them to operate with high precision (Belousov et al., 2022). In contrast, the construction industry is project-based and temporary. Each site is unique and conditions vary between projects, which reduces the level of standardization and makes reliable execution of automated tasks more complex to achieve (Kuppusamy & Mariappan, 2021). These fundamental differences explain why the implementation of advanced robotic systems, such as humanoid robots, is more challenging in construction than in other industries.

These challenges become particularly evident when examining the nature of construction sites. These environments are highly dynamic, with layouts that continuously evolve, materials that are frequently moved and multiple activities occurring simultaneously. This level of variability makes it difficult for robotic systems to operate effectively, as they are typically limited in their ability to handle unexpected changes or incomplete information (Khan et al., 2025; Odugu et al., 2025). Closely related to this is the requirement for structured and reliable information. Humanoid robots need accurate positioning data, clearly defined tasks and machine-readable instructions to operate safely and efficiently. This contrasts from traditional construction practice, where flexibility and human judgement play a central role and where work is continuously adapted based on situational experience. Translating this type of tacit knowledge into formalized digital instructions therefore represents a key challenge for robotic implementation (Uthai et al., 2026; Wong Chong et al., 2022).

Beyond these environmental and informational challenges, several technical and organizational barriers also need to be considered. From a technical perspective, robots must comply with strict safety requirements, especially when operating close to humans, and questions regarding certification and liability in case of accidents remain unsolved (International Federation of Robotics, 2024). From an organizational perspective, high implementation costs and difficulties integrating robotic systems into existing workflows further limit adoption (International Federation of Robotics, 2024; KeyiRobot, 2025).

2.2 Core Capabilities for Construction Robotics

Humanoid robots require several core technological capabilities. These capabilities form the technical foundation that enables humanoid robots to perceive their environment, navigate within complex spaces, plan tasks, manipulate tools and materials and collaborate safely with human workers (Siciliano et al., 2010). The following sections describe the key technological capabilities in humanoid robots that enable such operation.

Although humanoid robots are used as a primary reference point in this study, it is important to note that many of the identified capabilities are not exclusive to humanoid systems. Instead, these capabilities represent general requirements for autonomous robotic systems operating in dynamic environments. Core functions such as perception, navigation and task planning are shared across different robotic platforms (Casini, 2022; Tafazzoli et al., 2024), and are therefore not limited to humanoid robots. Humanoid robots can therefore be understood as representing an advanced stage within a broader automation spectrum (Uthai et al., 2026). Consequently, the conceptual framework developed in this chapter is applicable beyond humanoid robots alone.

2.2.1 Perception

Perception is a fundamental capability for humanoid robots operating in construction environments, as it enables them to interpret and interact with complex and dynamic surroundings (Roychoudhury et al., 2023). It includes understanding both the internal state of the robot and the external environment. In humanoid robotics research, perception typically involves multiple sensing modalities such as vision, depth sensing and inertial feedback, where each modality contributes with different types of information about the environment and the robot's own state (Chen et al., 2025). Previously conducted research on perception has mainly focused on humanoids operating in controlled environments, but recent studies highlight the need for combined perception systems that can cope with the unstructured and constantly changing nature of construction sites (Roychoudhury et al., 2023; Uthai et al., 2026).

Various technologies can be employed to enable perception in humanoid robots. Computer vision constitutes a central component, as it allows robots to extract semantic information from camera images. Computer vision systems are often based on deep-learning techniques that can detect objects and contribute to scene understanding in real-time. This capability is particularly important in construction environments, where robots must be able to identify tools, structural elements and human workers on site (Zhu et al., 2025).

However, camera systems alone are sensitive to physical disturbances such as variable lighting conditions, dust and reflections (Chen et al., 2025). To enhance visual perception, depth sensors such as Light Detection And Ranging (LiDAR) can provide three-dimensional spatial information by measuring distances to surrounding surfaces. LiDAR uses laser pulses to generate dense point clouds representing the geometry of the environment (Waykar, 2022), making it particularly useful in continuously changing settings. One limitation of LiDAR is that it mainly captures geometric information without semantic meaning (Chen et al., 2025). This illustrates the need to combine multiple sensing modalities in order for the robot to form a coherent understanding of its surroundings. The integration of multiple sensor inputs is commonly referred to as sensor fusion, which improves robustness and reliability in robotic perception systems (Chen et al., 2025; Uthai et al., 2026).

Beyond understanding the external environment, humanoid robots also rely on internal sensing to estimate their own body configuration, joint angles, velocities and contact forces. Internal sensing is essential for maintaining balance and enabling safe interaction with tools, human workers and other objects. Such sensing is typically achieved through encoders, inertial measurement units (IMUs) and force-torque sensors distributed across the robot's body, which provides continuous feedback on the robot's physical state (Roychoudhury et al., 2023).

2.2.2 Localization and Navigation

Localization is an essential robotic capability that enables robots to determine their position and orientation within an environment. Accurate localization is therefore a prerequisite for navigation, as it allows the robot to maintain spatial awareness in complex and dynamically changing surroundings such as construction sites. Based on this spatial understanding, navigation refers to the planning and execution of movement paths toward a specified destination while continuously accounting for obstacles and other environmental constraints (Roychoudhury et al., 2023). Figure 2.2 illustrates the robot Lola performing such movement planning and navigation in a laboratory environment.

A commonly applied framework for achieving localization and navigation is Simultaneous Localization and Mapping (SLAM). SLAM enables the robot to gradually build a map of its surroundings while simultaneously estimating its own position within that map. This process relies on features detected through perception sensors such as cameras or LiDAR. Through continuous map updates, the robot can adapt to environmental changes and maintain accurate spatial awareness (Chen et al., 2025). Consequently, localization and navigation depend directly on perception systems to detect features and support mapping and state estimation (Roychoudhury et al., 2023). This dependency becomes particularly critical in unstructured environments such as construction sites, where reliable perception and spatial understanding are required for safe movement and operation (Odugu et al., 2025).

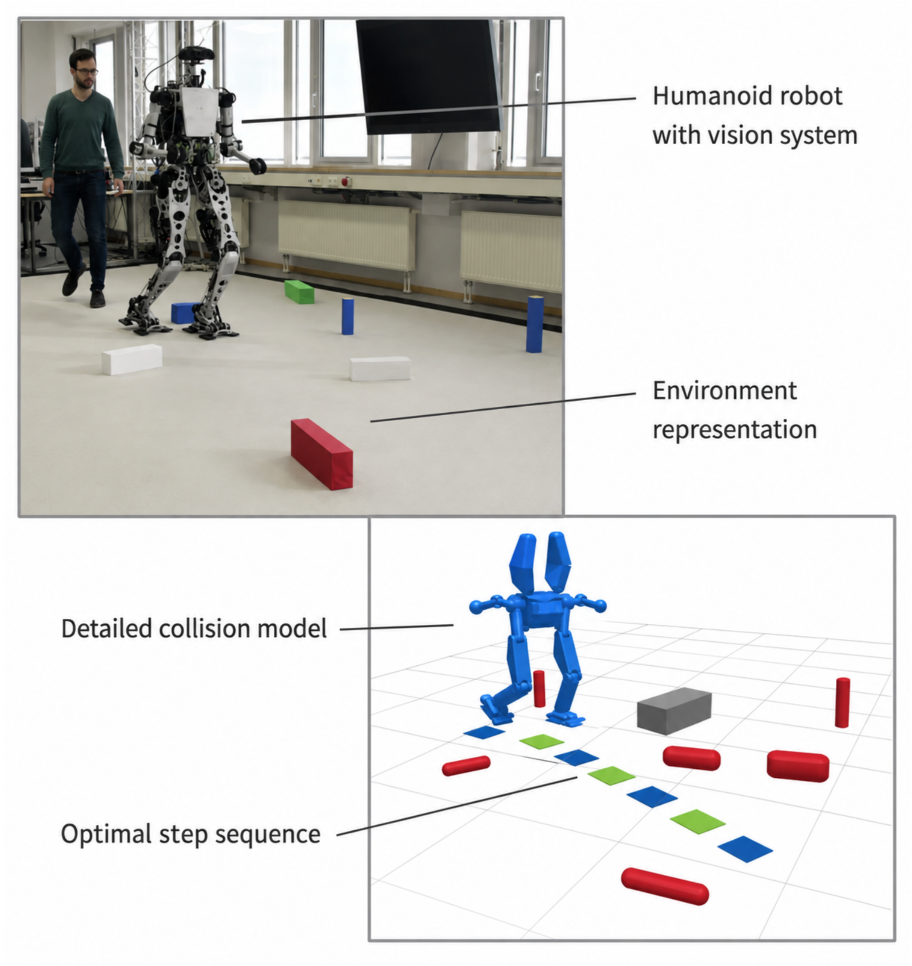

Figure 2.2: The upper-left image shows a robot being tested in a laboratory environment, while the lower-right image illustrates the robot's collision model, detected obstacles and ideal step sequence. The figure is inspired by Hildebrandt et al. (2019).

2.2.3 Task Planning and Decision-Making

Task planning and decision-making represent key capabilities for humanoid robots operating in construction environments where tasks vary in structure and context (Zhao et al., 2024). Unlike task-specific industrial robots that execute predefined and repetitive motions (Europe, n.d.; International Organization for Standardization, n.d.-b), humanoid robots are expected to perform a wide range of activities that require adaptability and contextual awareness, such as drilling, assembly and material transportation (Casini, 2022).

In modern robotic systems, AI-assisted planning approaches are increasingly used to support task planning and coordination between perception and motion execution. Task planning systems therefore allow the robot to deconstruct high-level objectives into executable sequences of actions such as grasping, turning, positioning and assembling components (Kim et al., 2021). In robotics literature, task planning is often described as the process of selecting and sequencing actions to achieve a desired state, thereby linking perception data with motion execution systems (LaValle, 2006).

Technologically, task planning in humanoid robots relies on motion planning frameworks that determine possible transitions between an initial and a goal state within a defined space (LaValle, 2006), which is illustrated in Figure 2.3. These frameworks integrate both kinematic and dynamic constraints of the robot, including joint limits, stability and reachability. At the same time, they incorporate logical and temporal considerations at the task-planning level, enabling robotic systems to coordinate actions and adapt task execution in dynamic construction environments (Zhao et al., 2024).

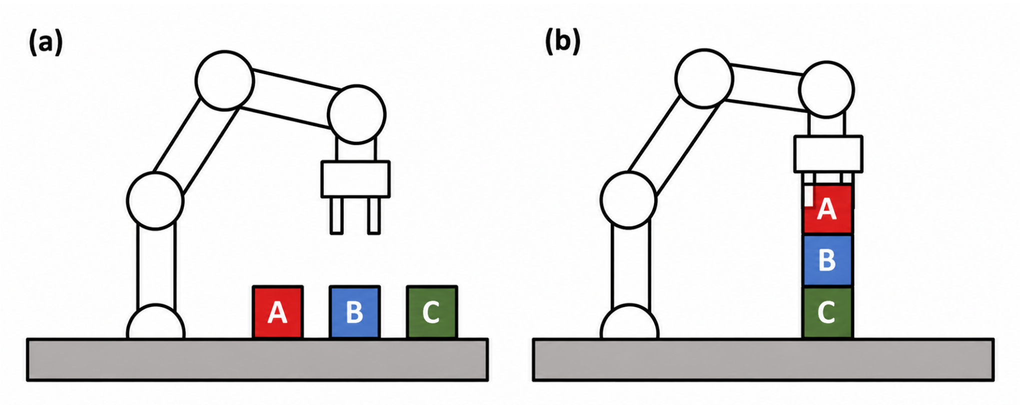

Figure 2.3: Example of robotic task planning where (a) shows initial state and (b) an alternative end state. The figure is inspired by Zhao et al. (2024).

2.2.4 Manipulation and Task Execution

Manipulation in robotics refers to the controlled physical interaction between a robot and external objects, including grasping, repositioning, assembling and tool use (Siciliano et al., 2010). In the context of on-site construction, manipulation enables humanoid robots to interact with tools, materials and building elements. Since humanoid robots are intended to operate in environments originally designed for humans, they must be capable of handling conventional construction tools and performing tasks that require dexterity, coordination and adaptability. This places particular emphasis on the design and control of the robot's end-effectors, often referred to as the robot's "hands", as well as on integrated sensing systems that provide feedback during physical interaction (Uthai et al., 2026).

Figure 2.4: Different types of end-effectors or "hands". Reprinted from Uthai et al. (2026), under CC BY-NC-ND 4.0.

To address these challenges, compliant or soft robotic fingers are often used, as they improve frictional contact and enable stronger grip stability by generating friction torque at the contact surface (Raessa et al., 2020). Combined with force-torque sensors and real-time control algorithms, these technologies enable humanoid robots to perform controlled and adaptive tool handling in unstructured environments (Uthai et al., 2026; Zhao et al., 2024).

2.2.5 Collaboration and Safety

For humanoid robots to operate effectively in construction environments, they must be capable of collaborating safely and efficiently with human workers. Human-robot collaboration (HRC) is therefore an important aspect of construction robotics, as it has the potential to enhance productivity, flexibility and safety while maintaining human supervision in complex tasks (Liu et al., 2025). According to Liu et al. (2025, p. 2), HRC can be described as *"people and robots jointly working on a construction site, forming a dynamic system to accomplish construction tasks"*.

In changing construction environments, such collaboration depends on technological systems that enable real-time awareness of human presence and motion (Villani et al., 2018). As construction sites involve unpredictable movements of workers, equipment and materials, humanoid robots must rely on systems such as LiDAR, depth cameras and tracking technologies to detect nearby workers (Chen et al., 2025). Sensor fusion approaches are commonly used as they combine several inputs, which improves robustness under varying environmental conditions (Roychoudhury et al., 2023). Real-time motion planning algorithms can then adjust the robot's path, velocity and force output in order to avoid collisions or reduce impact forces during close interaction with humans (Villani et al., 2018).

To formalize safety requirements, international safety standards such as ISO 10218 and ISO/TS 15066 have been developed for industrial and collaborative robots. These standards introduce principles such as speed, power and force limiting as well as protective stop mechanisms. They also establish acceptable values for contact forces and outline procedures for risk assessment when humans and robots operate in proximity to each other (International Organization for Standardization, n.d.-a, n.d.-b). Although these standards were originally developed for industrial manufacturing environments, they provide an important regulatory foundation for the future integration of humanoid robots in construction (Bock, 2015).

2.3 BIM and Digital Information for Robotics

The implementation of robotic systems in construction is not only dependent on technological capabilities but also on the availability of structured and reliable information. In this context, Building Information Modeling (BIM) plays a central role as a digital information environment that can support the integration of robotics into construction processes (Bock, 2015). BIM enables the structuring, storage and exchange of necessary information which is essential for automated and robotic task execution (Eastman et al., 2018).

This section therefore examines how BIM and digital information can support robotic construction processes. It focuses on BIM as an information environment, the role of machine-readable information and the interaction between digital models and robotic systems.

2.3.1 BIM as an Information Environment

BIM is used to create and manage digital models of buildings. It helps different project participants share and coordinate information throughout the project. By storing information in one model, BIM supports design, planning and construction and makes it easier to use the same information across different project phases. BIM can also support automated and robotic construction processes (Kim & Peavy, 2022; Wang et al., 2024). If the model contains clear and structured information, it can potentially be used by machines for tasks such as positioning, geometric interpretation and understanding relationships between building elements (Odugu et al., 2025).

Several BIM applications already support partial automation, such as quantity take-off, clash detection and rule-based model checking (Lee et al., 2025). These forms of automation primarily support design and coordination rather than direct physical execution on construction sites. In more highly digitalized production environments, such as digital fabrication and 3D printing, detailed BIM models enable a stronger link between design and manufacturing. In these cases, a high level of model detail during the design phase can support partially automated production processes (Tibaut et al., 2016).

For humanoid robots, this distinction becomes critical. Human workers can interpret incomplete drawings, adapt to unexpected site conditions and make decisions based on experience, while automated systems depend on precise and machine-readable information (Wilkins & Kiviniemi, 2008). Coordinates, tolerances, geometry and semantic descriptions therefore need to be clearly defined in digital models, as ambiguities may limit the functionality of robotic systems (Kim & Peavy, 2022; Wong

Chong et al., 2022).

Automation in BIM environments can follow different approaches. Rule-based systems rely on predefined logic and structured inputs, while machine-learning approaches are capable of handling more complex and uncertain situations (Soto Garcia et al., 2025). Regardless of the approach, both depend on reliable digital information structures that allow automated systems to interpret and act on the model data (Kim & Peavy, 2022; Wong Chong et al., 2022).

2.3.2 Information Requirements for Robotic Execution

To support robotic execution in construction, BIM models must provide a higher level of structure and detail than is typically needed for human interpretation. Robotic systems depend on clearly defined digital information in order to interpret building components, navigate within the environment and execute tasks reliably (Bock, 2015).

One important requirement concerns the alignment between the physical construction site and its digital representation. For robotic systems to interact reliably with the built environment, BIM models must provide both geometrically accurate and semantically consistent information. This includes accurate geometric representations positioned within a consistent coordinate system, as successful robotic implementation depends on reliable spatial correspondence between the digital model and physical site conditions (Odugu et al., 2025; Wong Chong et al., 2022). In addition to geometric accuracy, semantic consistency is required, as BIM models store object-level metadata linked to geometry, including type definitions and categorical information (Kim & Peavy, 2022). When robots detect physical elements on site through perception systems, these observations must correspond to clearly defined digital objects in the BIM model. If elements are inconsistently named, insufficiently categorized or represented only as generic geometry, the link between physical components and their digital representations becomes ambiguous, which may hinder reliable recognition and task execution (Wong Chong et al., 2022).

Furthermore, robotic execution depends on additional information beyond geometric and semantic representation. Robotic manipulation and assembly tasks require physical and material properties to be available in the BIM model, such as material type, weight, surface characteristics and connection logic, which influence how robotic systems grasp, position and assemble building components (Eastman et al., 2018). Geometric precision and tolerance information are also critical, as small deviations between digital representations and physical components may affect alignment accuracy or grasp stability (Belousov et al., 2022). In addition, robotic execution depends on construction sequencing information, where BIM models can contain scheduling data and installation logic through 4D modeling, which links digital building components to construction sequences. This information can support robotic planning algorithms by defining task dependencies, spatial constraints and installation order. By extracting object properties, spatial relationships and sequencing logic from BIM models, robotic systems can translate design intent into executable task instructions (Kim et al., 2021).

2.3.3 BIM-Robot Integration

The integration of BIM with robotic systems involves linking digital building models to robotic planning and execution processes. In BIM-integrated workflows, digital models can serve as a basis for defining robot positions, task sequences and movement paths, while human workers supervise and coordinate the execution process (Wang et al., 2024).

Research shows that BIM data can be connected to robotic simulation environments to generate and evaluate task sequences before physical execution. Through this integration, object properties, spatial constraints and assembly logic stored in the BIM model can be translated into executable robotic actions. In this sense, BIM functions not only as documentation, but also as a knowledge base that supports robotic decision-making and planning processes (Kim et al., 2021).

Beyond technical modeling requirements, BIM-robot integration also introduces implications for organizational processes. As robotic systems depend on reliable digital information, procedures are required for updating BIM models with as-built conditions and managing the exchange of sensor data between robots and digital models (Odugu et al., 2025). Validating semantic annotations is also necessary to ensure consistency and reliability of digital information structures (Kim & Peavy, 2022). Interdisciplinary collaboration between designers, engineers, site managers and robotic operators therefore becomes critical to ensure that digital information structures remain consistent throughout the construction process (Eastman et al., 2018; Sacks et al., 2020).

2.3.4 Digital Twins and Real-Time data

Construction environments change continuously as structures are assembled, materials are moved and temporary installations are introduced. These dynamic conditions may create discrepancies between planned BIM geometry and the actual state of the construction site (Sacks et al., 2020).

Digital twin frameworks have been proposed as a method for maintaining alignment between digital models and physical environments. A digital twin represents a continuously updated digital replica of the physical construction site, where sensor data and real-time monitoring systems are used to synchronize the digital model with the current state of the project (Wang et al., 2024). Such synchronization is particularly important for robotic systems operating in variable environments. Differences between planned geometry and actual site conditions may otherwise introduce localization errors or inconsistencies in robotic planning (Odugu et al., 2025). Continuous model updates help reduce spatial misalignment and improve coordination between digital representations and physical conditions (Sacks et al., 2020).

Digital twin systems also support closed-loop coordination between robotic systems and human supervisors. Real-time feedback from sensors and robotic platforms can be compared with the digital model, allowing task plans to be adjusted when deviations occur (Wang et al., 2024). In practice, decision-making in construction robotics often remain hybrid in nature, combining algorithmic planning with human judgement and supervision (Uthai et al., 2026).

2.4 Construction Requirements for Robotic Systems

While core robotic technologies define what humanoid robots are technically capable of, their successful implementation in construction also depends on the characteristics of the construction environment itself. Construction sites differ significantly from the controlled environments in which most industrial robots operate. They are typically dynamic, spatially constrained and continuously evolving as construction progresses (Bock, 2015; Liu et al., 2025).

For humanoid robots to operate reliably in such environments, certain physical, organizational and regulatory conditions must be fulfilled. These requirements concern both the physical structure of construction sites and the broader institutional frameworks that govern construction work (Odugu et al., 2025; Uthai et al., 2026). The following sections therefore outline key construction-related requirements that influence the feasibility of implementing humanoid robotic systems in on-site construction.

2.4.1 Construction Characteristics

Construction projects are typically characterized by high variability, temporary work environments and frequent changes in site conditions (Oesterreich & Teuteberg, 2016). Unlike industrial production environments, where workflows are highly standardized and spatial layouts remain largely constant, construction sites evolve continuously as work progresses. This dynamic nature creates challenges for robotic systems, as they rely on stable environmental references and predictable working conditions to function effectively (Bock, 2015). Human workers, in contrast, are able to adapt to incomplete information, unexpected obstacles and changing spatial configurations through experience and situational judgement (Wilkins & Kiviniemi, 2008).

Construction work further involves a high degree of parallel activities, where multiple trades operate simultaneously within shared spaces (Oesterreich & Teuteberg, 2016). Material transport, installation work and equipment operation often overlap both spatially and temporally, creating complex interaction patterns that must be coordinated and managed on site (Bock, 2015). These conditions increase the level of spatial and operational complexity that robotic systems must be able to interpret and navigate safely (Bock, 2015; Oesterreich & Teuteberg, 2016).

Another important characteristic of construction projects is the temporary nature of site organization (Koskela, 2000). Working zones, storage areas and access routes are frequently reorganized as construction progresses. While such flexibility allows human workers to adapt efficiently to changing project conditions, it introduces additional uncertainty for robotic systems that depend on spatial references and predictable material flows (Oesterreich & Teuteberg, 2016).

2.4.2 Physical Construction Site Requirements

One fundamental requirement concerns environmental stability. Humanoid robots rely on stable terrain, predictable ground conditions and controlled environmental variation to maintain balance and perform manipulation tasks (Uthai et al., 2026). As mentioned, construction sites are typically characterized by uneven surfaces, temporary installations and continuous reorganization. Enabling humanoid robots would therefore likely require more even walking paths, clearly defined working zones and reduced spontaneous reconfiguration of materials and equipment.

Organization and cleanliness also affect environmental stability. Robotic perception systems based on cameras and LiDAR are sensitive to obstacles, clutter and rapidly changing surroundings (Chen et al., 2025; Uthai et al., 2026). In unstructured environments, perception errors can increase, affecting both task accuracy and safety. This implies that construction sites would likely need more structured material placement, standardized logistic flows and potentially regular site scanning to update digital representations.

Safety zoning is also critical, as humanoid robots are expected to operate in close proximity to human workers (Nguyen et al., 2018). This introduces requirements for clearly defined safety zones, integrated sensor systems for collision avoidance and formalized protocols for human–robot interaction. Emergency stop systems and regulatory compliance mechanisms would also be necessary to ensure safe coexistence between human workers and autonomous systems (Bock, 2015; International Organization for Standardization, n.d.-b).

2.4.3 Legal and Regulatory Requirements

The introduction of humanoid robots in construction raises important legal and regulatory questions related to responsibility and accountability. In conventional construction projects, responsibility is typically clearly allocated between designers, contractors and equipment suppliers (Eastman et al., 2018). If a humanoid robot performs tasks autonomously based on digital instructions, the question of accountability becomes more complex (Tafazzoli et al., 2024). Responsibility could potentially lie with the designer who created the BIM model, the contractor operating the robot, the manufacturer of the robotic platform or the software developer responsible for the control algorithms. The increasing integration of artificial intelligence (AI) further complicates this issue, as autonomous decision-making may not always be directly traceable to a single actor. This suggests that existing liability frameworks may require clarification or adaptation (European Commission, 2020).

In addition to liability concerns, safety regulations represent a critical regulatory dimension. Construction sites are governed by strict work environment regulations intended to protect human workers. The introduction of humanoid robots would require compliance with machinery directives, CE marking requirements and emerging AI-related legislation such as the EU AI Act (European Parliament, 2024). The CE marking requirements ensure that machinery complies with EU safety and health regulations before being placed on the market, requiring risk assessment, documentation and conformity declaration (European Parliament, 2024). Certification processes would need to ensure that humanoid systems can operate safely in dynamic environments alongside human workers (International Organization for Standardization, n.d.-a, n.d.-b). Current safety standards are largely developed for either human labor or conventional automated machinery, and may not fully address autonomous humanoid systems performing complex on-site tasks (European Commission, 2020).

Another important regulatory question concerns the role of legally binding project documentation. In many construction projects today, 2D drawings remain legally binding documents, while BIM models function primarily as coordination tools (Eastman et al., 2018). If a humanoid robot executes work directly based on a BIM model, the legal status of the model becomes critical (Simonian & Korman, 2010). This raises the question of whether BIM models would need to become legally binding in order to ensure accountability and execution reliability.

2.5 Classification of Robotic Capabilities

Based on the literature presented in the framework of reference, robotic capabilities can be categorized into different functional layers with increasing levels of complexity. The classification shown in Table 2.1 summarizes key capability domains identified in previous research and links them to their technological basis and functional role in humanoid robotic systems.

Table 2.1: Summary of the key capability layers in humanoid robots and their corresponding complexity level, based on the literature presented in the framework of reference.

Capability Layer	Technology	Function	Complexity Level	Reference
1. Proprioception	Internal sensing	Enables the robot to control its own joints and body position	Very low	(Roychoudhury et al., 2023)
2. Physical interaction	Force-Torque sensors	Measures forces during contact with tools or materials	Low	(Roychoudhury et al., 2023)
3. Spatial perception	LiDAR	Creates 3D maps of the environment and enables navigation	Medium	(Chen et al., 2025)
4. Visual perception	Computer vision	Identifies objects, tools, and construction elements	Medium	(Zhu et al., 2025)
5. BIM integration	Digital twin	Links robot perception with the BIM model	High	(Wang et al., 2024)
6. Cognitive control	Decision-making / Task planning	Integrated perception and planning to select actions	Very high	(LaValle, 2006)

The complexity levels reflect increasing requirements in terms of environmental understanding, system integration and decision-making capabilities. Lower-level capabilities rely primarily on internal control and limited interaction with the environment, whereas higher-level capabilities require integration of perception, digital information and adaptive planning.

From a construction perspective, this implies that more advanced robotic applications are not only dependent on technological development, but also on increasingly structured environments, reliable BIM data and standardized processes. The capability layers therefore form a cumulative hierarchy where higher levels build upon and depend on the successful integration of lower-level functions.

While the classification is based on humanoid robotic systems, it reflects general requirements for increasing levels of automation in construction. This hierarchy provides the foundation for the analytical framework developed in Section 2.6, where capability complexity is linked to system-level requirements in construction.

2.6 Analytical Framework

The classification of robotic capabilities presented in Table 2.1 provides a structured understanding of what humanoid robots must be able to perform in construction environments. However, these capabilities alone are not sufficient for implementation, as they must be translated into corresponding requirements within the construction system. While previous sections describe technological capabilities and construction conditions separately, there is a need to integrate these perspectives in a more systematic way. To enable this connection, an analytical framework is developed that links robotic capabilities to requirements across four key system dimensions: informational prerequisites, physical conditions, process structures and organizational factors. These dimensions represent the core components of construction project environments and align with the research questions of this study.

While the classification identifies several distinct capability layers, some of these operate at similar levels. To enable analytical application, they are therefore grouped into broader capability domains which represent functional categories that are more suitable for analyzing construction requirements. The resulting capability domains used in this framework are: (1) perception and state awareness, (2) physical interaction, (3) cognitive control and (4) BIM integration. The framework is structured as a matrix where each capability domain is analyzed in relation to the four system dimensions. This enables a systematic identification of how robotic capabilities translate into specific requirements on construction sites, BIM models, processes and organizational structures.

The analytical framework serves as the link between theory and empirical analysis and has two main purposes. First, it guides the coding and analysis of empirical data. Second, it provides the foundation for structuring the results and for developing the automation ladder presented in the discussion.

Table 2.2: Analytical framework for robotics and autonomous systems in construction.

	Information	**Physical**	**Process**	**Organization**
Perception and State Awareness	Requires accurate, up-to-date and machine-readable data representing geometry, position and state	Requires visibility, accessibility and reduced uncertainty in the environment	Requires continuous data updates and alignment between digital and physical states	Requires responsibility for data accuracy and maintenance
Physical Interaction	Requires detailed geometric and material information, including tolerances	Requires controlled conditions, stable elements and predictable interfaces	Requires clearly defined tasks and standardized execution sequences	Requires competencies related to robotic operation and supervision
Cognitive Control	Requires structured and semantically rich BIM data enabling decision-making	Requires structured and predictable workspaces	Requires predefined workflows and sequencing logic	Requires planning roles and coordination structures
BIM integration	Requires interoperable, structured and machine-readable BIM models	Requires alignment between digital models and the physical site	Requires integration between BIM and construction workflows	Requires governance of data, standards and responsibilities

3
Research Design

This chapter explains the research perspective and methodology of the study, as well as how the literature study was carried out and how interviews were conducted with professionals working with management, production and automation in construction.

3.1 Research Perspective

This thesis takes the perspective of a future scenario in which humanoid robots, rather than single-purpose autonomous systems, are employed in the construction industry. This approach is based on the rapid development of robotic technologies and the integration of artificial intelligence (Uthai et al., 2026). Previous studies also suggest that the complexity and dynamic nature of construction environments favor more flexible (Külz et al., 2025), human-like robotic systems, as alternative approaches would require significant adaptation of construction sites or the use of multiple specialized systems for different tasks (Kim et al., 2021; Uthai et al., 2026).

This perspective affects the scope of the study, as the focus is placed on identifying future requirements for construction environments rather than analyzing current large-scale implementations. The study therefore explores what conditions must be fulfilled for humanoid robots to operate effectively, rather than evaluating existing solutions.

3.2 Research Approach

Building on the defined research perspective, this study adopts a qualitative research approach to investigate the implications of introducing humanoid robots into construction environments. The qualitative approach enables an in-depth exploration of complex and interrelated factors, including technological capabilities, organizational structures and regulatory frameworks (Creswell & Creswell, 2018).

The research follows a deductive approach (Bryman, 2016). Existing research on humanoid robotic capabilities is the starting point for the study, and these are structured through the analytical framework to identify corresponding construction requirements. The study asks what conditions must be fulfilled in order for humanoid robots to operate effectively in construction environments, based on this translation of capabilities into system requirements.

To address this question, the research uses triangulation by combining three main components: a literature review, expert interviews and a case application. This approach contributes to a broader understanding of the topic and enhances the credibility of the findings (Carter et al., 2014). The literature review provides the theoretical foundation for understanding humanoid robots and their technological capabilities. Expert interviews provide industry perspectives on the challenges and opportunities associated with robotic implementation in construction. The findings are then applied to a construction project to explore how current practices relate to the requirements identified in the study.

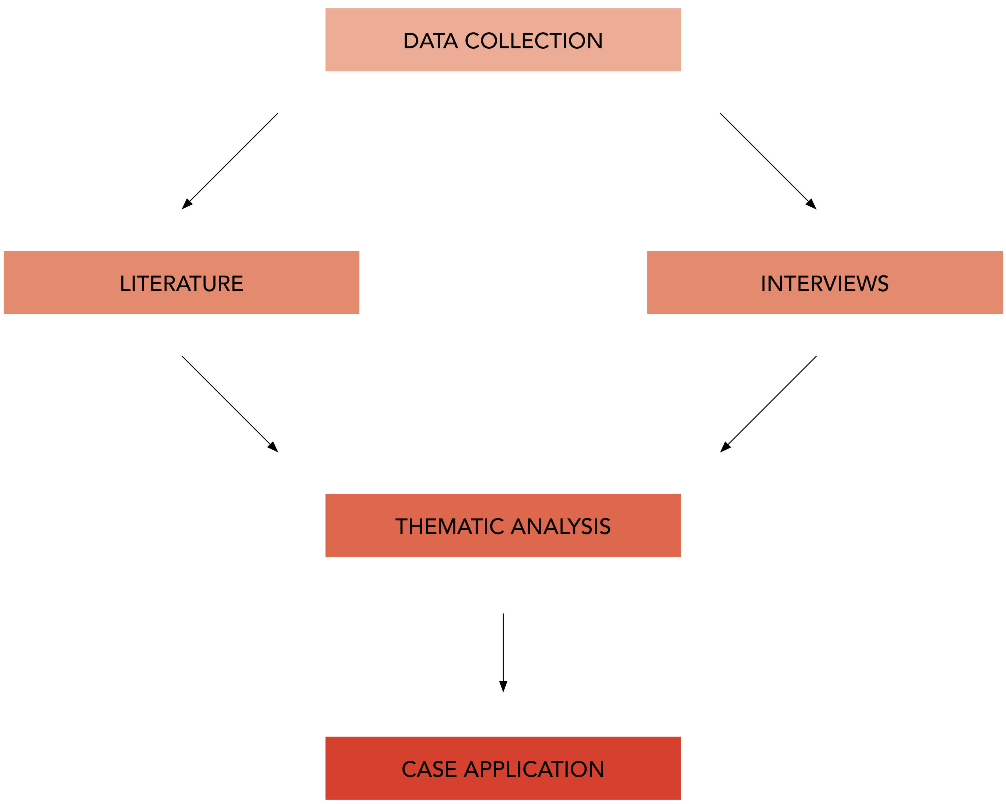

Figure 3.1: Diagram showing the research process.

3.3 Data Collection

Data for this study were collected in two phases: a literature review followed by semi-structured interviews with industry and research experts. The literature review was conducted first to establish a theoretical understanding of humanoid robots in construction, which then informed the design of the interview guide and the selection of relevant empirical focus areas. This combination of data sources is commonly used in qualitative research to integrate theoretical perspectives with empirical insights from practice (Creswell & Creswell, 2018).

3.3.1 Literature Study

A literature study was conducted to identify existing research on humanoid robots, construction robotics, BIM integration and human–robot collaboration. Scientific databases such as Google Scholar and Scopus were used to locate peer-reviewed journal articles and conference papers related to these topics. The search was performed using combinations of keywords such as "humanoid robots", "construction robotics", "construction automation", "human-robot collaboration", "Building Information Modeling (BIM)" and "construction processes", including variations and synonyms of these terms.

The literature selection was guided by the need to understand the technological capabilities required for humanoid robots in construction environments, as well as the corresponding conditions in BIM systems and construction processes. This theoretical focus was chosen as humanoid robot implementation depends not only on robotic capabilities, but also on how these capabilities interact with digital information structures and construction site conditions.

The findings from the literature study were used to develop the analytical framework presented in Section 2.6 and provided the theoretical foundation for the empirical analysis.

3.3.2 Interviews

To complement the literature study, a total of 11 semi-structured interviews were conducted with experts working in robotics, BIM innovation and construction production. Semi-structured interviews were chosen as they allow predefined topics to be discussed while also giving participants the flexibility to share their perspectives (Bryman, 2016).

The interviews were conducted after the literature study in order to explore how the requirements identified in previous research relate to current industry practices and perceptions. Two interview guides were developed: one tailored for respondents from robotics and technology-focused companies, and one tailored for respondents from construction companies. The different guides were used to account for the differing perspectives and areas of expertise of the participants. The full interview guides are provided in Appendix B and Appendix A. The interviews focused on technological readiness, BIM information requirements, construction site conditions and organizational challenges related to the future implementation of humanoid robots in construction. The participants were selected based on their expertise in robotics, digital construction processes, BIM or construction production management.

The interviews were conducted online and lasted approximately 60 minutes. With the consent of the participants, the interviews were recorded and later transcribed to support the analysis.

3.4 Data Analysis

The interview data collected in this study were analyzed using thematic analysis, a qualitative method for identifying and interpreting patterns within textual data (Braun & Clarke, 2006). The purpose of the analysis was to identify key requirements and challenges related to the implementation of humanoid robots in construction, based on expert perspectives.

The analysis followed an iterative process inspired by the six phases of thematic analysis proposed by Braun and Clarke (2006), but was adapted to fit the research design of this study. After the interviews were conducted, all recordings were transcribed. The transcripts were then read multiple times to ensure familiarity with the content and to gain an overall understanding of the data.

The coding process was guided by the analytical framework developed from the framework of reference. In the initial stage of coding, relevant segments of the interview transcripts were identified and assigned primary codes based on the broader system dimensions defined in the analytical framework, such as informational, physical, process and organizational aspects. In a second step, secondary codes were applied to further specify the content of each segment by linking statements to specific robotic capability layers identified in the framework of references, such as perception, interaction, BIM integration and cognitive control. This two-level coding approach enabled a systematic connection between empirical observations and theoretical constructs, where data were organized in a structured way in relation to the key dimensions of the study.

Following the coding process, the data were structured according to the primary coding categories derived from the analytical framework. Rather than generating entirely new themes, the analysis focused on deepening, refining and strengthening these predefined categories based on empirical insights from the interviews. The results are therefore presented according to these four system dimensions, which serve as the main analytical structure of the study. This approach ensures a clear link between the theoretical framework, the empirical data and the resulting analysis.

3.5 Case Application

In addition to the literature review and interviews, the study includes a case application. The purpose of the case application is to examine how the identified requirements for humanoid robot implementation relate to existing construction practices. Case-based approaches are often used to explore complex phenomena in real-world contexts to identify gaps between theoretical concepts and practical conditions (Yin, 2017). In this study, the case application was used to evaluate how current construction processes, BIM practices and organizational structures align with the requirements identified in the theoretical and empirical analysis.

The case application focuses on a selected construction project within the company Byggstyrning. The company was selected due to its structured use of BIM and digital planning processes, making it a relevant context for examining the practical implications of humanoid robot integration in construction.

3.6 Ethical Considerations

The study follows ethical guidelines for research involving human participants, including informed consent, voluntary participation, anonymization and secure data handling (Bryman, 2016). Before each interview, participants had the opportunity to review a consent form stating the aim of the study, how the data would be used, as well as how it would be stored and deleted upon completion of the study. The form also states their right to withdraw their consent at any time without consequences. To ensure accuracy and transparency, interviewees were given the opportunity to review relevant excerpts before inclusion in the final thesis. Recordings of interviews were only made after explicit consent from the participants. All recordings and transcripts were deleted once the study had been completed to ensure confidentiality and data protection.

3.7 Artificial Intelligence Disclosure

Artificial Intelligence (AI) tools were used throughout the thesis as a supportive aid in the writing, transcription and literature search process. The use of AI was limited to three tools: ChatGPT (OpenAI, Free and Paid versions, GPT-3.5 and GPT-4-based versions), Scopus AI and Chalmers AI. ChatGPT was used for language-related support, such as grammar checking, spelling correction and suggestions for alternative wording and phrasing. It was also used to support the refinement of academic formulations and to assist in clarifying methodological descriptions and theoretical discussions. Scopus AI was used as a complementary tool to support the identification and exploration of relevant scientific literature within the Scopus database, particularly for gaining an overview of research areas and identifying potential keywords. Chalmers AI was used for the transcription of interview recordings.

However, AI was not used for data processing, empirical analysis or interpretation of results. All theoretical development, literature handling, analysis and final conclusions were carried out by the authors.

4 Results

This chapter presents the requirements for implementing humanoid robots in construction derived from the empirical data. The results are structured according to the four system dimensions defined in the analytical framework: informational prerequisites, physical conditions, process structures and organizational factors. While the analysis is centered around robotic systems, the identified requirements are also considered relevant for broader autonomous systems in construction, such as monitoring technologies, drones and data-driven control systems.

4.1 Overview of Empirical Data

The empirical data consists of 11 interviews with representatives from companies working with construction, robotic and automation technologies as well as researchers within BIM and robotics. Their roles and type of company are shown in Table 4.1. These interviewees were selected to give a broad perspective on both practical construction processes and technological development which is important for understanding the requirements for implementing robotic systems.

Table 4.1: Interviewees and their roles.

Interviewee	Type of company	Role
A	Construction	Research and innovation manager
B	Automation and robotic technologies	BIM innovation manager
C	Construction and technological university	Industrial PhD student
D	Construction	Research and innovation manager
E	Construction	Production manager
F	Trade association	Industry development manager
G	Construction	Project manager
H	Technological university	Project manager at the department of computer science
I	Technological university	Associate professor of adaptive systems
J	Ventilation subcontractor	Construction engineer
K	Automation and robotic technologies	Business developer for robotics

4.2 Informational Prerequisites

The interviews highlight the importance of having detailed and structured digital information as a prerequisite for the implementation of robotic and autonomous systems in construction. Several respondents emphasized that current BIM models are often not developed to a sufficient level of detail to support automated processes. A BIM innovation manager at a robotics company noted that *"you need to have a very detailed BIM model... suited for fabrication"* [B], where information such as drilling points, element geometry and task specifications are clearly defined. Interviewee H, who is conducting research on robotics in construction, complemented this perspective by stating that *"BIM is not currently designed for robotic work, it is designed to document a building model"*. The interviewee further emphasized that the BIM model would need to move beyond documentation and become an execution-oriented information environment, stating that *"all robots need a work instruction, and BIM needs to function as a digital format for work instructions for machines and humans"*. These interview contributions indicate that current BIM practices may need adjustments for the implementation of advanced robotic systems to be feasible.

This view is not shared by all respondents. In contrast to interviewees working specifically with robotics, who believe that the BIM information included today is not sufficient for robotic execution, a project manager mentions technology as the main barrier to autonomous systems. The interviewee noted that when technology and artificial intelligence are sufficiently advanced for autonomous movements and decision-making in dynamic environments, the information available today may be enough. This suggests that the perceived limitation may lie either in the structure of the information or the capability of the technology to utilize it.

Apart from containing sufficient and relevant data, the digital information must also be clearly structured and gathered in one place accessible for all disciplines involved. This means that the data must be organized in a consistent and standardized way with clear object definitions, naming conventions and relationships between elements. Interviewee B explains that without this structure, the information is difficult for robotic systems to interpret. This requirement is also shown in how robots interact with digital information in practice. A robotics researcher explained that *"the robot must connect to a digital blueprint or a digital BIM model, find its tasks there and perform them when someone tells it to do so"* [H], expressing the need for BIM to function as a direct interface for task execution.

Several interviewees mentioned challenges related to information responsibility. Increased levels of detail and structure are required but it is often unclear who is responsible for creating, updating and maintaining this information. Interviewee C and G noted that in many current projects, the BIM models are developed across multiple disciplines and responsibilities are distributed between designers, engineers and contractors. This creates uncertainty when more detailed and machine-readable data is needed because no single actor is clearly responsible for ensuring that the information meets the requirements for robotic execution.

Some interviewees brought up specific requirements related to how information is used in practice. Interviewee B further explained that robots must be able to interpret spatial information, stating that *"it must relate to a coordinate system and understand where it is on the construction site"*. Interviewee A discussed the importance of real-time data and up-to-date information about the construction site to make sure that tasks are carried out under the right conditions. Interviewees B and C further emphasized the need for structured data, where information is organized in a consistent and machine-readable way.

4.3 Physical Conditions

Several interviewees emphasized the challenges posed by the physical conditions at construction sites and mentioning their unpredictable and constantly changing nature. As interviewee B stated, *"you have a dynamic environment because job sites change more or less daily"* and another interviewee working at a robotics company explained that *"robots require sufficient, clearly organized space to operate effectively"* [K], which illustrates the complexity of the surroundings that humanoid robots must be able to navigate and operate within. Similar challenges are also relevant for other autonomous systems operating on construction sites, particularly those relying on navigation and real-time environmental interaction.

Another recurrent issue mentioned across multiple interviews was the presence of dirt, mud and exposure to weather elements. One interviewee suggested that covering construction robots with protective clothing could help prevent excessive accumulation of dust and dirt and thereby mitigating environmental wear and tear. In contrast, interviewee E, who works as a production manager, stated that *"it's no problem that it [the work site] needs to be clean"*, referring to the advantages of the company's internal logistics processes. These processes ensure that materials are not left on site and that new materials are delivered on a weekly basis. In addition, a team-spirit is created among different disciplines, where each team is responsible for maintaining a defined work zone. This creates an incentive to leave the workspace in a clean and orderly condition, as each team expects to begin new tasks in a similarly prepared environment.

Interviewee E addresses another physical challenge, as it is noted that *"they want finished floors, smooth floors, and we have hollow-core slabs... the floor is uneven"* [E]. This highlights a limitation of current construction environments, where the use of hollow-core slabs and fast-paced building methods often results in uneven surfaces that may constrain the deployment of robotic systems. Although, the interviewee expanded on this by arguing that structured logistics systems with clearly defined work zones and regular material deliveries can reduce clutter and create more predictable working environments, which may better support robotic operation.

4.4 Process Structures

The dynamic and constantly changing nature of construction sites also influences which tasks respondents consider suitable for robotic execution. Multiple interviewees suggested that repetitive and low-skilled tasks, which do not require craft-specific expertise, are the most promising areas for implementing autonomous systems. Physically demanding and hazardous tasks were also brought up as suitable applications as robotic systems could reduce the risk of injuries and improve working conditions. This implies a restructuring of task allocation within construction processes, where robots are primarily assigned standardized and physically intensive activities, while human workers retain responsibility for tasks requiring creativity, problem-solving and contextual judgment. One interviewee working with implementation of construction robotics expressed that *"it's important for humans to have these creative and fun roles, and for them to be preserved"* [H].

Interviewee C added another perspective on process requirements in relation to scheduling and coordination of construction activities. The interviewee highlighted takt planning, a time-location based scheduling method (Tommelein & Emdanat, 2022), as a way of structuring both time and space in construction processes planned for robotic execution. In this context, it was noted that *"more projects have delivery time frames"*, indicating that time-related information is increasingly formalized and integrated into project planning. This suggests that, in addition to spatial and geometric considerations, the way time is structured within construction processes is important for coordinating robotic tasks and enabling autonomous execution.

Beyond planned scheduling and static process structures, several interviews highlight the increasing importance of real-time data collection and continuous scanning of the construction site. Interviewee H described this as a process challenge, explaining that much of the required planning information is still held by people rather than digital systems: *"the site manager has the schedule in their head and knows which work has been done where and when"*. A research and innovation manager at a construction company also identified *"monitoring of the construction site and progress tracking"* [D] as applications that are probably not very far into the future. Autonomous and robotic systems rely on up-to-date environmental information, typically gathered through sensors, scanning technologies or other forms of live data capture, in order to ensure that actions are aligned with current site conditions. Interviewee A emphasized scanning as an integrated part of project progress control, ensuring that a robot does not initiate a task *"...before the previous one has been completed and approved"*. In this sense, scanning also functions as a form of continuous verification and documentation, supporting both operational sequencing and quality assurance within autonomous workflows.

These requirements are not only relevant for humanoid robots but also for other autonomous systems, where process structures increasingly rely on continuous real-time data and dynamic updates. At a systemic level, this introduces a shift from static planning towards continuously adjusted workflows, where task sequencing and coordination are informed by ongoing site conditions and project progress. Interviewee F highlighted this complexity by noting that *"you often have to think through every moment and how it should be handled"*, illustrating the lack of predefined and standardized process structures in construction. However, the effectiveness of such real-time coordination depends on how information is governed, shared and updated across organizational boundaries.

4.5 Organizational Factors

The interviews indicate that the implementation of robotic systems in construction is also an organizational challenge. Several respondents emphasized that changes in planning, project organization and work processes are required to enable effective use of robotic and autonomous systems on construction sites. Interviewee D, who works with innovation at a construction company, emphasized that robotic systems must be integrated into existing site practices, stating that *"it needs to be integrated into the working methods used on the construction site"*. An organizational challenge identified by an interviewee working at the construction industry's trade association is the risk associated with implementing new technologies, explaining that testing new solutions may affect production outcomes and introduce uncertainties.

A recurring aspect in the interviews is the need for earlier and more detailed planning. Interviewee B highlighted that robotic systems require a higher level of preparation compared to traditional construction processes, as many decision that are typically made on-site must instead be defined in advance. This is also supported by a business developer at a robotics company who stated that *"organizations need to enable earlier and more detailed planning to support robotics"* [K]. This shifts effort from the production phase to the design and planning phases, increasing the importance of coordination between different actors in the project.

In connection to this, two interviewees expressed the importance of considering the information flow, who has access to the information and who can edit it to make sure that data is accurate and up to date for robotic execution to be safe, correct and effective. An industry development manager at the construction trade association also pointed out that many construction companies lack dedicated research and development capacity, especially smaller firms, and this limits their ability to invest in and adopt new robotic technologies. It was noted by one interviewee that advanced robotic and autonomous systems would require the information to be gathered in a *"shared database"* [C] for different departments to be coordinated and to provide an information base for automated systems to work from. Adding to this perspective, the collaboration between several actors was seen as a challenge by an innovation manager at a construction company, who noted that the complexity of establishing common approaches increases with the number of stakeholders involved in construction projects, making alignment of goals, responsibilities and working methods more difficult in practice.

The interviews collectively show that the successful implementation of robotic systems is highly dependent on organizational coordination across project phases, disciplines and stakeholders where changes in planning practices, information governance and collaboration structures are required in parallel.

4.6 Summary of Main Findings

This section provides a compiled overview of the coded interview data presented in Table 4.2. The table shows how individual interview excerpts were categorized according to the primary system dimensions and related capability layers defined in the analytical framework.

The contribution of codes shows that the empirical data spans across all four system dimensions with a strong emphasis on physical conditions and organizational factors. Physical conditions are frequently associated with perception and state awareness with the importance of environmental constraints in construction contexts. In contrast, organizational factors and process structures are primarily linked to cognitive control, reflecting the importance of planning, coordination and decision-making in enabling robotic execution.

Information-related statements are mainly connected to BIM integration and the role of digital information structures as a foundation for automation. However, several excerpts also demonstrate overlap between categories, indicating that many empirical observations relate to multiple system dimensions simultaneously. This shows the interconnected nature of information, processes and organizational structures in construction environments.

The coding results support the analytical framework by illustrating how robotic implementation challenges emerge across multiple interdependent dimensions rather than within isolated categories. This suggests that the identified requirements are not limited to specific robotic applications but are also applicable to more integrated autonomous systems, where multiple technologies interact across different stages of the construction process.

Table 4.2: Coded interview excerpts from the thematic analysis.

Quote	**Code**	**Theme**
"BIM is not currently designed for robotic work, it is designed to document a building model" [H]	Information	BIM integration
"you need to have a very detailed BIM model... suited for fabrication" [B]	Information	BIM integration
"...if information is gathered in a structured way" [C]	Information	BIM integration
"if artificial intelligence advances at such a rapid pace, then once we've figured out how to let robots move freely in a highly dynamic environment, we'll have come so far that the information currently in the model will be sufficient" [G]	Information	Cognitive control
"all robots need a work instruction, and BIM needs to function as a digital format for work instructions for machines and humans" [H]	Information	BIM integration
"the robot must connect to a digital blueprint or a digital BIM model, find its tasks there and perform them when someone tells it to do so" [H]	Information	BIM integration

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Quote	Code	Theme
"it must relate to a coordinate system and understand where it is on the construction site." [B]	Information	Perception and state awareness
"...mud, weather and wind" [A]	Physical	Perception and state awareness
"monitoring of the construction site and progress tracking" [D]	Physical	BIM integration
"you have a dynamic environment because work sites change more or less daily" [B]	Physical	Perception and state awareness
"robots require sufficient, clearly organized space to operate effectively" [K]	Physical	Perception and state awareness
"they'll probably need to wear clothes, otherwise they'll be too exposed to dirt" [H]	Physical	Perception and state awareness
"it is often dusty, dirty and exposed to the elements" [D]	Physical	Perception and state awareness
"it's no problem that it [the work site] needs to be clean" [E]	Physical	Perception and state awareness
"they want finished floors, smooth floors, and we have hollow-core slabs... the floor is uneven" [E]	Physical	Physical interaction
"more projects have delivery time frames" [C]	Process	Cognitive control
"...without engaging in a craft" [C]	Process	Cognitive control
"it's important for humans to have these creative and fun roles, and for them to be preserved" [H]	Process	Cognitive control
"need to scan the site continuously" [A]	Process	Perception and state awareness
"low skilled work" [C]	Process	Cognitive control
"you often have to think through every moment and how it should be handled" [F]	Process	Cognitive control

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Quote	**Code**	**Theme**
"the site manager has the schedule in their head and knows which work has been done where and when" [H]	Process	Cognitive control
"...so that it does not start an activity before the previous one has been completed and approved" [A]	Process	Cognitive control
"using a robot requires way more preplanning" [B]	Organization	Cognitive control
"must review the work preparation process" [C]	Organization	Cognitive control
"personal responsibility is not resolved" [A]	Organization	Physical interaction
"shared database" [C]	Organization	BIM integration
"we also have a fragmented construction industry with many different players who need to collaborate, which makes it even more complex to put together a solution" [D]	Organization	BIM integration
"organizations need to enable earlier and more detailed planning to support robotics" [K]	Organization	BIM integration
"it needs to be integrated into the working methods used on the construction site" [D]	Organization	Cognitive control

5
Case Application

This chapter applies the requirements identified in the literature and interviews to a case company in order to examine how current construction practices align with the conditions required for humanoid robot integration. The case application focuses on two central aspects of the construction process: work preparation and BIM practices. The purpose is to identify gaps between current practices and the requirements derived from the analytical framework and to explore how these processes may need to evolve to support higher levels of automation.

5.1 Case and Task Description

The case application of this thesis is made in collaboration with the company Byggstyrning. Byggstyrning is a Swedish construction management company working throughout the entire construction process, from early design phases to building production. The company is characterized by its focus on innovative and digital solutions for design, production and management (Byggstyrning, n.d.).

The case and task selection was made in collaboration with the thesis supervisor and representatives from Byggstyrning, with the intention of identifying a project that is both relevant to the research focus and representative of the company's contemporary construction practices. The selected case is LUMI, an office building located in Uppsala (see Figure 5.1), characterized by a high degree of reused materials. The project provides a relevant context for exploring how current construction processes and BIM practices relate to the requirements for increased automation and potential robotic implementation.

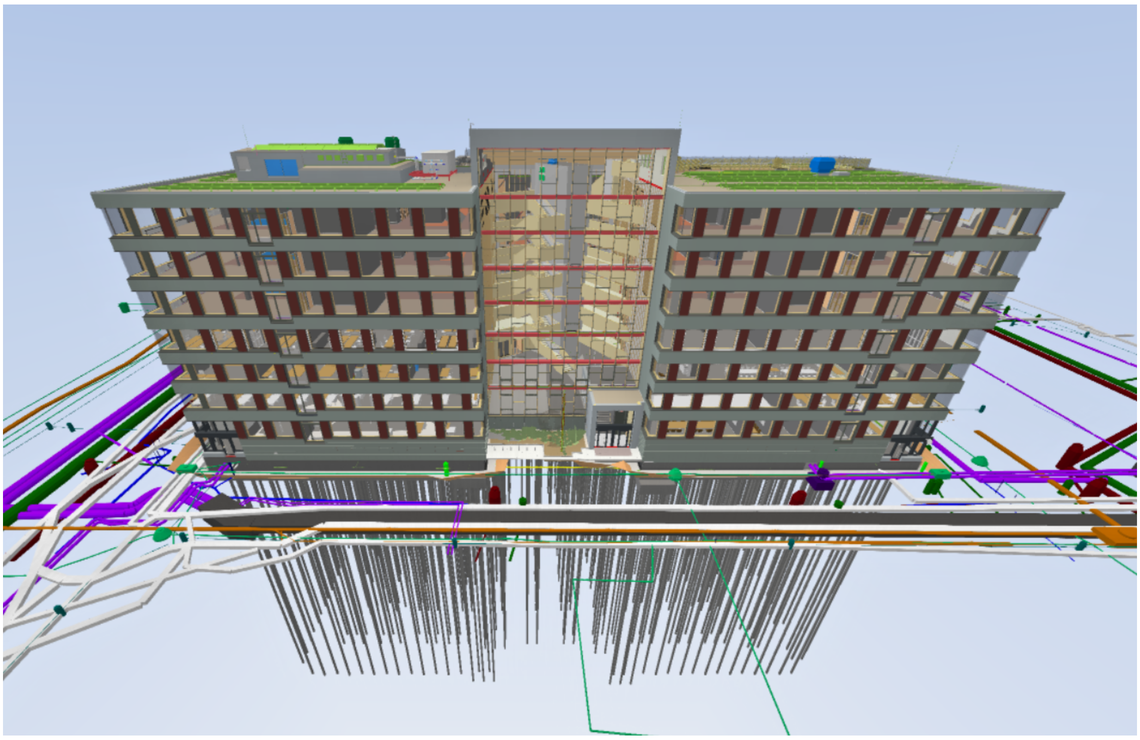

Figure 5.1: 3D view of the LUMI building. Screenshot from the BIM model provided by Byggstyrning.

In order to limit the scope of the case application, a specific construction task was selected for analysis within the project. The selected task is the installation of gypsum boards in ceilings. This task was identified as particularly relevant due to its physically demanding nature by employees at Byggstyrning and was further emphasized by several interviewees, making it a potential candidate for robotic implementation. In the context of the case project, this task is carried out in 16 sanitary spaces across four floors, where ceiling areas span between 1.5 - 6.9m^2 per space (see Figure 5.2 and Figure 5.3). The uncut gypsum boards are 12.5 millimeters thick and have a dimension of 1200x2400 millimeters giving them a weight of 28.8 kilograms. The ceiling areas are also characterized by the presence of multiple technical installations, making it a representative setting for analyzing both spatial constraints and task complexity in relation to robotic execution.

Figure 5.2: 2D view of floor 8 with sanitary spaces marked in red. Adapted screenshot from the BIM model provided by Byggstyrning.

Figure 5.3: Area of sanitary spaces in the south wing of floor 8. Adapted screenshot from the BIM model provided by Byggstyrning.

The scope of the task is further limited to the transportation, cutting and installation of gypsum boards in the ceiling. It is assumed that all preceding installations within the ceiling, such as electrical and mechanical systems, have already been completed prior to this stage. This delimitation enables a focused analysis of the installation process itself, without accounting for interactions with parallel or preceding construction activities.

5.1.1 Work Preparation

To gain insight into Byggstyrning's work preparation process for ceiling gypsum board installation, a meeting was conducted with the project manager of the LUMI project. The following section summarizes the key findings from this discussion.

In the case project, as well as in most of Byggstyrning's projects, takt planning is applied as a central scheduling method. The construction process is organized into defined work zones, where materials are delivered to specific zones on a weekly basis. The workflow is planned so that the delivered materials are installed within the same time frame, after which the work area is cleared before the construction workers move on to the next zone.

As the installation of gypsum boards is considered a relatively simple task, the work preparation is not formally documented but instead communicated verbally to the plaster contractor. Apart from specifying a minimum board length for each room, Byggstyrning does not provide detailed instructions regarding measurements, cutting strategies or material handling and placement within the work area. Instead, this knowledge is assumed to reside within the contractor, who is given flexibility to determine how the gypsum boards are cut and installed based on experience, without predefined requirements regarding cut placement or board usage.

In addition, the organization of work is based on teams with shared responsibility for each zone. This creates a system of mutual accountability, where teams are expected to maintain a level of order and cleanliness that facilitates subsequent work by others. As a result, the construction site is characterized by relatively structured material flows, reduced clutter and a higher level of spatial organization compared to more conventional construction practices.

These scheduling processes are documented in a shared Excel file, which is continuously updated by project stakeholders to reflect changes in the construction process. For ceiling gypsum board installation, the contractor performs the work after all technical installations, such as ventilation, mechanical and plumbing systems, have been completed. The installation process therefore requires adaptation of the gypsum boards, including cutting openings to accommodate these systems. Requirements for this adaptation are also not specified by Byggstyrning, and decisions regarding how the boards are adjusted are instead left to the contractor.

This highlights that while the construction process is structured at a macro level, the specific work preparation for this task relies heavily on tacit knowledge and flexible execution rather than standardized or explicitly defined procedures.

5.1.2 BIM Practices

The BIM model used in the case project contains structured information describing the ceiling system, primarily intended to support design coordination, documentation and communication between project stakeholders, including architects, structural engineers and technical consultants such as ventilation, plumbing and mechanical contractors. The ceiling is modeled as a compound element, defined as a gypsum ceiling system (UT01-01) with classification according to systems such as BSAB (43.E/40) and IFC (covering type). The model contains several types of information. Identity and classification data are provided, including type name, type ID and descriptions of the ceiling system. Performance-related properties are also included, such as sound class and material-related descriptions. The model also contains references to external databases, such as dRofus, where further technical documentation and specifications can be accessed.

This type of information indicates that the BIM model is well developed in terms of documentation. The use of classification systems and linked data supports coordination and life cycle management, which are important aspects in contemporary construction projects. The model helps stakeholders understand what type of system is used and how it relates to other project information. However, while the model is well developed for documentation and coordination purposes, it does not provide the level of detail or structure required for direct robotic execution.

5.2 Gap Analysis

The gap analysis compares the requirements for humanoid robotic execution identified in Chapter 2 and Chapter 4 with the current practices observed in the case project. This includes both the BIM model and the work preparation process within the selected task scope. By analyzing these aspects collectively, the aim is to identify variations between how the task is currently planned and executed, and how it would need to be defined and structured to enable robotic implementation.

5.2.1 BIM-Related Gaps

As shown in Table 5.1, one major gap in the BIM model is the level of geometric detail. The ceiling in the current model is represented as one continuous element. This level of detail may be insufficient for robotic execution as the robot would likely need information about each individual gypsum board, including its size, position and orientation. Without this level of detail, it may be difficult for the robot to determine where and how each board should be installed.

Another important gap is the lack of installation logic. The BIM model does not describe how the ceiling should be constructed. There is no information about where to start, in what order the boards should be installed or how they relate to each other. In the current process, such decisions are made by workers on-site based on experience. Similarly, there is also a lack of production-related information. For example, the model does not include data on how the gypsum boards should be cut, what dimensions are required or what tolerances should be applied. These decisions are typically made during construction, but for robotic execution, this information must be clearly defined in advance.

Table 5.1: BIM-related gap analysis of gypsum board ceiling installation.

Requirement	**Current BIM Practice**	**Gap**
Geometric detail	General ceiling type defined	No individual board geometry or placement
Installation logic	Not defined	No sequence or mounting logic
Cutting data	Not included	No production-level information
Semantic clarity	Basic classification exists	Not structured for robotic interpretation
Material data	Basic properties included	Insufficient for robotic handling
Process information	Not included	No link between model and workflow
Model–site alignment	Assumed	No real-time validation

The BIM model lacks process-related information connected to the workflow itself. There is no information describing task dependencies, execution stages or coordination between different activities. In the current construction process, this knowledge is largely managed by workers and site management during production. However, for robotic implementation, the workflow and process structure would need to be predefined and connected to the model in a more systematic way. Although the BIM model includes classification and descriptive data, this information is primarily intended for human interpretation. It supports understanding of what the element is, but not how it should be constructed. As a result, the model is not structured in a way that supports automated execution. The material-related information included in the BIM model is limited to basic properties intended for coordination and documentation purposes. Information relevant for robotic handling, such as board weight, gripping surfaces or handling constraints, is not included. The semantic structure of the model also presents limitations. Classification systems and descriptive naming conventions are used but the information is not organized in a machine-readable way adapted for robotic interpretation. As a result, the robot may have difficulties understanding the function, sequence and relationship between different building components without additional structuring of the model data.

5.2.2 Process and Organizational Gaps

In addition to the BIM-related gaps, several gaps are identified in the case company's current construction processes. Work instructions for the selected task are primarily communicated verbally during weekly meetings. While this approach allows for flexibility, it creates challenges for automated systems which require explicit, structured and machine-readable instructions in order to perform tasks. Furthermore, many decisions are based on the expertise and experience of construction workers. This tacit knowledge enables efficient problem-solving in practice but is not directly transferable to robotic systems. For robotic implementation, such knowledge must be formalized, structured and digitally represented. As shown in Table 5.2, these gaps are closely related to how work instructions and decision-making are currently handled in the case project.

Another challenge relates to the use of takt planning. While takt planning provides a structured and predictable workflow that is beneficial for robotic execution, its current implementation is not directly compatible with automated systems. In the case project, takt planning is managed through Excel-based schedules which are not integrated with the BIM model. For robotic implementation, a direct link between planning data and the digital model would be required. This also highlights a broader gap related to model-site integration. Robotic execution depends on accurate positioning and alignment between the digital model and the physical construction site. This requires real-time data capture and continuous validation of site conditions, which is currently not part of the case company's processes.

Table 5.2: Process-related gap analysis of gypsum board ceiling installation.

Requirement	**Current Practice**	**Gap**
Work instructions	Verbally communicated	No formalized or machine-readable instructions
Decision-making logic	Based on contractor experience	Tacit knowledge not captured or transferable
Planning integration	Excel-based takt planning	No direct link between schedule and model

5.3 Future Scenario

In order to address the gaps identified in Table 5.1 and Table 5.2, a future scenario is proposed to illustrate how the work preparation process and BIM practices could be adapted to enable humanoid robots to perform ceiling installation in the case project. The scenario focuses on how the current workflow would need to evolve in terms of planning, information and execution. The purpose is to illustrate what conditions must be in place for a humanoid robot to carry out a specific task, in this case cutting and installing gypsum boards in the ceiling.

5.3.1 Work Preparation

In the proposed scenario, the work preparation process undergoes significant changes in order to support robotic execution. While certain existing practices, such as takt planning, provide a strong foundation, additional adaptations are required to address the process-related challenges identified in the case.

The use of takt planning, which is already implemented in the case company, supports the structuring and sequencing of work in a way that is beneficial for robotic execution. By organizing the construction process into defined zones and time intervals, a predictable workflow is created where tasks are performed in a controlled and repeatable manner. This reduces variability in the production process and facilitates the planning of robotic operations. In addition, the associated emphasis on maintaining clean and organized workspaces minimizes obstacles and environmental uncertainty, which are critical factors for reliable robotic perception and navigation. However, to address the identified lack of integration between planning and execution, takt planning must be digitally linked to the BIM model. This allows robotic systems to interpret when and where tasks should be performed.

Another key aspect of the future scenario is the integration of real-time data. While work preparation defines the intended conditions for execution, construction sites are inherently dynamic and deviations from the plan are likely to occur. To handle such deviations, the robot must have access to up-to-date spatial information. This can be achieved through scanning and sensing systems as explained in Section 2.3.4, either integrated into the robot or provided through external systems operated by human workers. These systems enable continuous comparison between the planned and actual environment, allowing the robot to adjust its actions when necessary.

The introduction of robotic systems also implies new roles and responsibilities within the work preparation process. In addition to traditional planning activities, responsibility must be assigned for ensuring that digital information is accurate, complete and aligned with site conditions. For the case company, this involves new competencies related to data management, system supervision and coordination between digital and physical processes. These roles would need to work in close collaboration to the BIM developer already employed at the company, ensuring that the information required for robotic execution is properly defined and integrated into the BIM models. Work preparation thus becomes a more interdisciplinary activity, integrating construction planning with digital and technological considerations.

Overall, the future work preparation process is characterized by increased structure and a stronger integration between planning, digital information and execution. While existing practices such as takt planning provide a valuable starting point, additional developments are required to transform work preparation into a process capable of supporting robotic construction.

5.3.2 BIM Practices

In the future scenario, the BIM model plays a central role as a direct input for robotic execution, rather than only serving as a tool for design and coordination. In order to support the adapted work preparation process, the BIM model must therefore evolve from a descriptive representation of the building to an operational model that enables planning and execution. This implies a shift where the model not only defines what is to be built, but also how it should be constructed.

Compared to current practice, this requires a significantly higher level of geometric and production-related detail, which was emphasized by interviewee B. Instead of representing the ceiling as a single system, the model must include individual gypsum boards with exact dimensions, positions and orientations, allowing the robot to identify and interact with each component. In addition, the BIM model must include production-related information such as cutting data, tolerances and installation requirements. By incorporating this type of information, decisions that are currently made on-site based on experience can be predefined and structured within the model, thereby reducing reliance on tacit knowledge and enabling robotic execution.

Furthermore, the BIM model must include installation logic and sequencing. This involves defining the order in which tasks are performed, how elements depend on each other and how the robot should move and act within the space. To work autonomously, the robot must also know the locations of materials, machinery, and workstations. By linking this information to the takt planning structure used in the project, a direct connection between planning and execution can be established. This integration is essential for translating planning activities into actionable instructions for robotic systems.

In addition to increased detail and logic, the structure of the information requires adaptation to ensure that it is machine-readable and unambiguous. Data needs to be standardized, consistent and clearly defined, requiring improved object definitions and naming conventions compared to current practices. Finally, the BIM model must be continuously aligned with the physical construction site through the integration of real-time data. By combining the model with scanning and sensing systems, it becomes possible to validate and update the digital representation based on actual site conditions, which is necessary for accurate and reliable robotic execution.

Overall, the future BIM model becomes tightly integrated with both planning and execution processes, supporting a more structured, data-driven and coordinated approach to construction.

6 Discussion

This chapter discusses the findings of the study by connecting the literature, interview results and case application. The aim is to interpret the results and explain what they mean for the implementation of humanoid robots in construction.

6.1 From Robotic Capabilities to Construction Requirements

This section relates robotic capabilities identified in the literature to potential requirements on the construction system, structured through the analytical framework. It explains what must be in place for humanoid robots to operate efficiently in practice. A key finding of this study is that the implementation of robotic systems in construction depends on both the technology and to which extent the construction system is prepared to support and utilize these capabilities.

The literature on humanoid robotics shows that several advanced capabilities are required for robots to function in construction environments. Many studies highlight the importance of structured digital information and particularly BIM as a key enabler for robotic task execution (Bock, 2015; Eastman et al., 2018). From an informational perspective, the literature presented by Bock (2015) and Wilkins and Kiviniemi (2008) further emphasize that humanoid robots require highly structured, detailed and machine-readable data, including precise geometric, semantic and task-related information. However, the empirical findings and the case study indicate that current construction practices are not designed to provide this type of information. Several respondents emphasized that existing BIM models lack the level of detail and structure required for automated execution. Instead information is often incomplete, adapted for human interpretation and developed for coordination rather than execution. This creates a gap between theoretical requirements and practical conditions, where human workers are able to interpret incomplete drawings and adapt to unclear situations, while robots depend on precise and standardized input data. The findings therefore indicate that the main barrier is the mismatch between the level of information currently provided and the level required for robot execution and not the actual lack of digital tools. This highlights the need for BIM practices to evolve towards more standardized, detailed and production-oriented modeling approaches. This shift points to a transition from BIM as a coordination tool towards an operational platform capable of supporting automated and autonomous construction processes, which is consistent with previous research on

BIM-enabled robotic execution and semantic task planning (Kim & Peavy, 2022; Odugu et al., 2025; Wang et al., 2024).

This information gap is closely related to the physical and process-related conditions of construction projects. The different robotic capabilities explained in Section 2.2 create specific demands on the construction site environment. As described by Uthai et al. (2026) and Wong Chong et al. (2022), robotic systems require clearly defined tasks, sequences and constraints that are specified in advance. This presents a challenge, as variability and lack of standardization are inherent features of construction (Oesterreich & Teuteberg, 2016), which complicate the implementation of robotic systems. Similarly, the interview findings and the case study show that many decisions are made on site, are adapted continuously based on experience and are communicated verbally which makes them difficult to translate into digital systems. To enable humanoid robots, construction environments therefore need to become more controlled and organized, for example through defined working zones, improved logistics and clearer task structuring.

From an organizational perspective, and building on the capability requirements identified in the analytical framework, humanoid robotic systems introduce new demands on project organization, roles, responsibilities and competencies. As Odugu et al. (2025) explain, the integration of humanoid robots requires structured and continuously updated digital information, which requires coordination across multiple actors, including designers, engineers, site managers and technology providers (Eastman et al., 2018; Sacks et al., 2020). Consequently, responsibilities related to data accuracy, model management and system operation must be clearly defined, which was also emphasized in the interviews. The case study and interviews indicate that current project organizations are not fully structured to support this level of cross-disciplinary coordination, with responsibilities for digital information management often being fragmented and informally distributed across actors. This implies a shift toward stronger information governance structures and more formalized collaboration processes across project phases, ensuring that the informational requirements derived from robotic capabilities are consistently met in practice. For example, this could mean assigning clear responsibility for defining and maintaining task-related BIM data where designers provide detailed geometric and semantic information while contractors contribute production related data such as installation sequences and tolerances. Such structures would make sure that the information required for robotic execution is consistently defined, updated and accessible throughout the project lifecycle.

6.2 Industry Readiness

The empirical findings provide insights into how humanoid robots are perceived in the construction industry and how this perception relates to the requirements identified in the literature. Overall, the interviews indicate a positive attitude towards increased automation and the implementation of humanoid robots, particularly due to expected benefits such as higher productivity, improved safety and reduced labor shortages. These perceived benefits align with the opportunities outlined by Bock (2015) and Uthai et al. (2026), where humanoid robotics is presented as a potential response to key industry challenges. But at the same time, the empirical findings indicate a relatively low willingness to actual implementation due to factors like cost, maturity level and challenges with integration into excising workflows.

Interviewees highlighted concerns related to economic feasibility, technological maturity and integration into existing construction processes. Several respondents also linked these challenges to limitations in current BIM practices, particularly the lack of sufficiently structured and machine-readable information required for robotic execution. This reflects the theoretical requirement that robotic systems depend on highly detailed digital representations and clearly defined processes presented by Bock (2015). However, the interviewees differ in how they interpret the main barrier to implementation. Some participants viewed technological development as the primary limiting factor, arguing that implementation will follow once robots reach sufficient capability. Others emphasized that the main challenges lie within the construction system itself, including fragmented processes, dynamic site conditions and insufficiently structured BIM data, which is also highlighted in the literature. This is interesting because it shows that the problem is not clearly defined. Different actors focus on different barriers, which means that solutions are developed in isolation rather than together. This helps explain why implementation is slow and supports the idea that robotic adoption requires a system-level approach rather than improvements in one single area.

Since economic feasibility was identified as a barrier to implementation by Uthai et al. (2026), recent developments related to lower-cost humanoid robots, such as Tesla Optimus, may influence the future feasibility of robotic implementation in construction. Lower costs could reduce economic barriers and make humanoid robots more accessible not only for large construction firms but also for smaller companies with more limited investment capacity. The findings of this study suggest that affordability alone is unlikely to enable widespread adoption, as challenges related to BIM structure, process coordination and dynamic site conditions would still remain significant barriers.

The interviews also highlight a distinction between different types of automation. Task-specific robots, such as the Jaibot by Hilti, which are already used in controlled environments and included in previous studies on construction robotics (Bock, 2015; Kromoser & Reichenbach, 2021; Xu et al., 2021), were generally perceived as more mature and easier to implement. In contrast, humanoid robots intended to operate in dynamic on-site environments were associated with greater uncertainty and complexity, reflecting higher requirements in terms of adaptability, information integration and coordination. Instead of fully autonomous systems, incremental approaches such as semi-autonomous or supervised robotics were seen as more realistic in the short term, suggesting a gradual implementation pathway. This reflects how different types of robotic systems are associated with varying levels of system requirements, where more advanced systems demand greater alignment between information, processes and organizational structures.

The case study reinforces these findings by illustrating how current BIM models and project conditions do not fulfill the informational and process-related requirements identified in the theoretical framework. From a BIM perspective, the model contains structured documentation and classification data that is needed for human use, but lacks geometric detail, installation logic and production-related information required for robotic execution (Bock, 2015; Wilkins & Kiviniemi, 2008; Wong Chong et al., 2022). Similarly, the work preparation process relies heavily on verbal communication and contractor experience, where decisions regarding cutting, installation and adaptation are made on-site rather than being predefined.

This creates a mismatch between perceived potential and actual feasibility, which can be understood as a gap between current project conditions and the requirements associated with more advanced levels of automation, as the analyzed task does not represent a strong use case for humanoid robot implementation. Although the industry recognizes the potential for robotic systems, the current project conditions are not always sufficiently mature to support their effective use. These findings indicate that industry readiness depends on technological development and also the alignment between robotic requirements, BIM maturity, project-specific conditions and organizational structures.

The case highlights that not all construction tasks are equally suitable for automation. The analyzed task is relatively simple, limited in scope and relies on on-site adaptability, meaning that the benefits of robotic implementation may be limited in this context. This illustrates that even if a task is technically possible to automate, it is not necessarily economically or practically efficient. In larger or more complex scenarios involving repetitive handling, heavier materials or higher volumes, the potential benefits of robotic systems are believed to become more evident by several interviewees.

While the literature discusses the potential benefits of humanoid robots in various applications such as drilling and material transportation (Casini, 2022), the case further illustrates the importance of evaluating and comparing robotic and manual execution in relation to task conditions. This reflects that industry readiness is dependent on both technological capability and whether specific tasks justify the increased system requirements associated with higher levels of automation.

6.3 Development of the Automation Ladder

Based on the findings from the literature, interviews and case study, there is a need for a structured way to relate increasing levels of automation in construction to the system requirements identified in this study. This also helps to explain why technologies may be perceived differently in terms of maturity and readiness, as later discussed through the Gartner Hype Cycle. An *automation ladder* is developed as a conceptual model linking levels of robotic capability to construction system readiness across four dimensions presented in the analytical framework: information, physical conditions, process structures and organizational factors. It is intended as an analytical tool for interpreting how different levels of automation correspond to increasing system complexity and integration requirements.

6.3.1 Conceptual Foundation

The findings from both the literature review and empirical study indicate that the implementation of robotics in construction cannot be understood as a binary shift from manual work to full automation. Rather, it should be conceptualized as a gradual progression, where increasing robotic capability imposes higher requirements on the construction system.

As discussed in Chapter 2, robotic systems can be understood as a hierarchy of capabilities, ranging from basic physical interaction to advanced perception, decision-making and integration with digital systems such as BIM. While humanoid robots serve as a useful reference point, Casini (2022) and Tafazzoli et al. (2024) note that these capabilities are not exclusive to such systems but apply across a wide range of autonomous and semi-autonomous technologies. Importantly, these capabilities are cumulative, meaning higher-level functionalities depend on the integration of lower-level systems. This hierarchical structure implies that more advanced robotic applications require not only technological maturity, but also increasingly structured environments, reliable machine-readable information and well-coordinated processes.

The empirical findings strengthen this perspective by demonstrating clear differences in perceived feasibility between levels of autonomous systems. In addition, the results highlight that requirements related to information, physical conditions, process structures and organizational factors are strongly interdependent. This suggests that higher levels of automation cannot be achieved through isolated improvements but require alignment across the entire construction system.

These insights motivate a structured analytical framework relating robotic capability levels to construction system readiness from a system-level perspective. The automation ladder addresses this by synthesizing the system dimensions of information, physical conditions, process structures and organizational factors in the analytical framework into four key dimensions relevant for robotic implementation. These dimensions are based on the framework and supported by both literature and empirical findings, which point to recurring challenges related to information, site conditions, processes and coordination between project actors:

- BIM maturity and information structure
- Control and predictability of site conditions
- Standardization of construction processes
- Organizational integration and coordination

Rather than representing a fixed technological pathway, the automation ladder should be understood as an analytical tool for interpreting how increasing levels of automation correspond to increasing system complexity, task sophistication and integration requirements.

6.3.2 Description of the Levels

The automation ladder consists of four main levels representing different stages of automation in construction, where the highest level represents a future scenario based on speculations from the findings. Each level is characterized by a specific type of autonomous system and shows the corresponding requirements on the construction system.

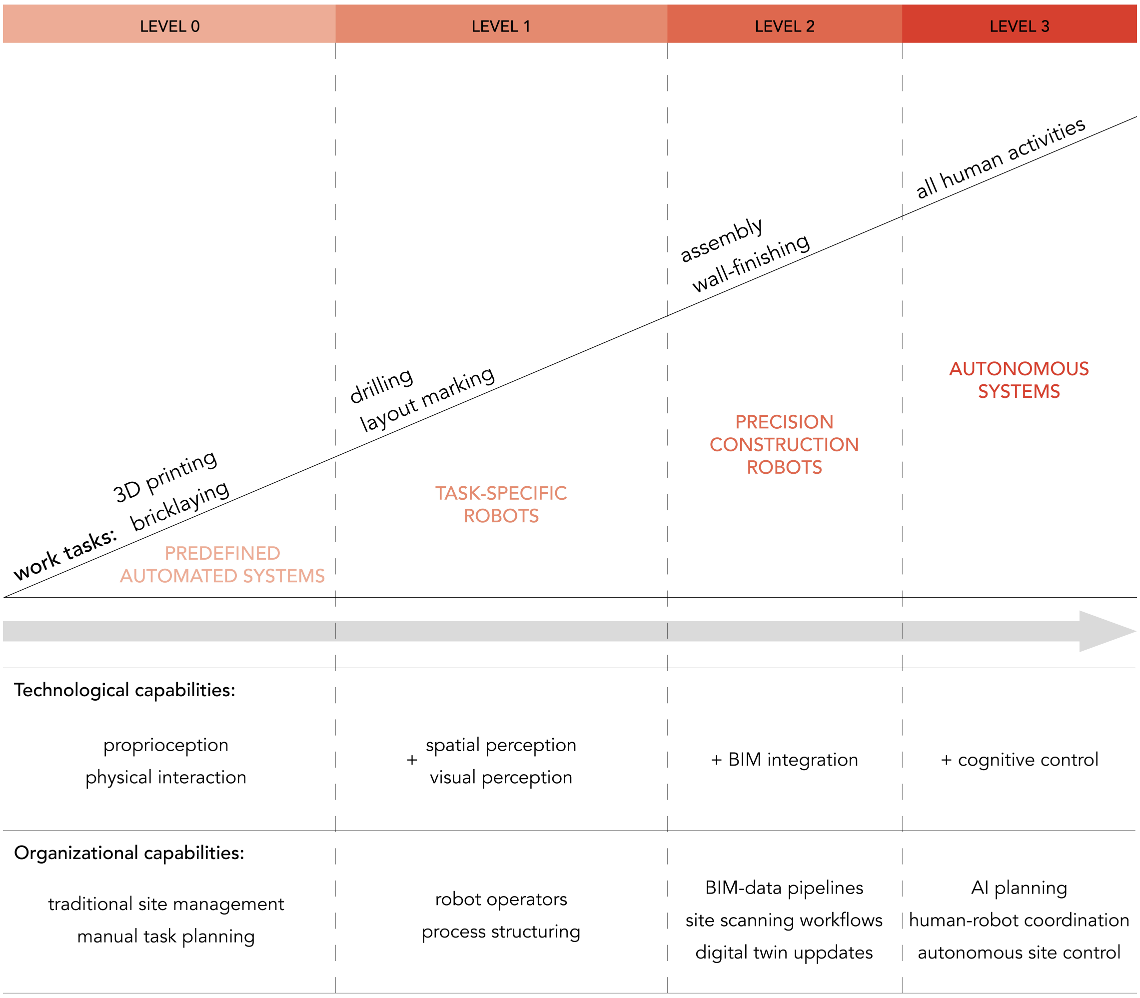

Figure 6.1: The automation ladder illustrates how higher levels of robotic capability require increasing construction system readiness.

Predefined robots

At the lowest level of the ladder are predefined automated systems, such as 3D printing or automated layout plotting. These systems operate based on fixed instructions and predefined paths with limited ability to adapt to changing conditions, consistent with descriptions of highly scripted construction automation systems in the literature (Casini, 2022; Li et al., 2025). As a result, the requirements on BIM, processes and site conditions are relatively low. Basic geometric information and predefined task inputs are often sufficient, and the systems typically operate in controlled environments with minimal interaction with other processes (Kromoser & Reichenbach, 2021; Tulke et al., 2025).

From an organizational perspective, these systems function primarily as tools that support existing workflows and require limited changes to roles or responsibilities (Bock, 2015; Oesterreich & Teuteberg, 2016).

Task-specific robots
The next level consists of task-specific robots designed to perform a single operation repeatedly, such as drilling or material placement. Examples include systems such as the Hilti Jaibot and similar task-focused construction robots that have been demonstrated in controlled field applications and research prototypes (Belousov et al., 2022; Hilti, n.d.; Xu et al., 2021). Compared to predefined systems, these robots require more structured and reliable input data, often derived from BIM models or positioning systems (Kim et al., 2021; Kim & Peavy, 2022). The importance of accurate and machine-readable information increases at this level (Kim & Peavy, 2022; Zhu et al., 2025). Tasks must be clearly defined and site conditions must be sufficiently controlled to ensure repeatability (Casini, 2022; Tibaut et al., 2016). Processes become more standardized and some degree of coordination between digital models and on-site execution is required (Jiang et al., 2022; Wang et al., 2024).

Organizationally, this level introduces new roles related to planning, monitoring and maintaining robotic systems, although human supervision remains central (Liu et al., 2025; Villani et al., 2018).

Precision construction robots
The third level includes more advanced robotic systems that require high spatial accuracy and closer integration with digital models. These systems build on developments in BIM-driven robotic planning and closed-loop construction feedback systems (Kim & Peavy, 2022; Sacks et al., 2020; Wang et al., 2024). These robots operate in environments where deviations between design and reality must be managed, often through sensing technologies such as scanning or real-time feedback (Chen et al., 2025; Waykar, 2022). BIM becomes a critical component at this stage, providing detailed geometric, semantic and task-related information (Odugu et al., 2025; Zhu et al., 2025). The alignment between digital and physical environments becomes essential and variations must be continuously managed (Sacks et al., 2020; Wang et al., 2024). Construction processes at this level require a higher degree of pre-planning and coordination, as tasks must be defined with precision and linked to digital information (Külz et al., 2025; Terzer et al., 2024). Site conditions must be more predictable and workflows must be structured to support robotic execution (Tafazzoli et al., 2024; Tulke et al., 2025).

From an organizational perspective, this level requires stronger integration between disciplines, clearer data governance and increased competence in digital construction methods (Karimi & Iordanova, 2021; Oesterreich & Teuteberg, 2016).

Autonomous systems

The highest level of the automation ladder has not yet been achieved in the construction industry, but is illustrated as a potential future development based on the findings. It contains autonomous systems, representing a shift from isolated robotic tools to integrated, system-wide automation in construction (Kang et al., 2024; Khan et al., 2025). This level includes not only advanced robotic systems such as humanoid robots, but also other autonomous systems such as drones, AI-based planning tools and real-time data-driven control systems (Jiang et al., 2022; Li et al., 2025; Odugu et al., 2025). This level of automation is characterized by the coordination of multiple autonomous technologies operating across different functions of the construction process (Sacks et al., 2020; Wang et al., 2024).

As a result, the requirements on the construction system increase significantly. BIM must evolve from a design tool into a central information hub containing structured, machine-readable and continuously updated data that can be used for planning, execution and feedback (Lee et al., 2025; Sacks et al., 2020). In addition, real-time data integration becomes essential, enabling autonomous systems to adapt to changing site conditions (Jiang et al., 2022; Wang et al., 2024). Physical site conditions must support both robotic execution and autonomous navigation and this requires a balance between standardization and flexibility (Bock, 2015; Casini, 2022).

Processes at this level shift towards a high degree of predefinition and digital coordination where tasks, sequences and decision rules are defined in advance and continuously updated based on incoming data (Külz et al., 2025; Wang et al., 2024). This reduces reliance on ad hoc decision-making and increases the importance of simulation, planning and control (LaValle, 2006; Zhao et al., 2024).

From an organizational perspective, this level represents a significant transformation. Responsibilities related to data management, system integration and decision-making become more centralized and clearly defined (Karimi & Iordanova, 2021; Oesterreich & Teuteberg, 2016). New competencies are required, particularly in areas such as data analytics, system management and digital coordination (Kang et al., 2024; Kuppusamy & Mariappan, 2021). As highlighted in the empirical findings, existing challenges related to fragmentation and unclear responsibilities become critical barriers to achieving this level of automation in construction.

6.4 Positioning Humanoid Robots within the Gartner Hype Cycle

The results of this study show a clear gap between how humanoid robots are perceived and how willing companies are to implement them in practice. This gap can be interpreted using the Gartner Hype Cycle, which describes how emerging technologies typically move from inflated expectations towards more realistic productivity-based adoption (Gartner, 2024). This framework has been widely used to understand the adoption trajectory of emerging technologies, particularly in fields characterized by high uncertainty and long implementation cycles, such as construction (Bock, 2015; Oesterreich & Teuteberg, 2016).

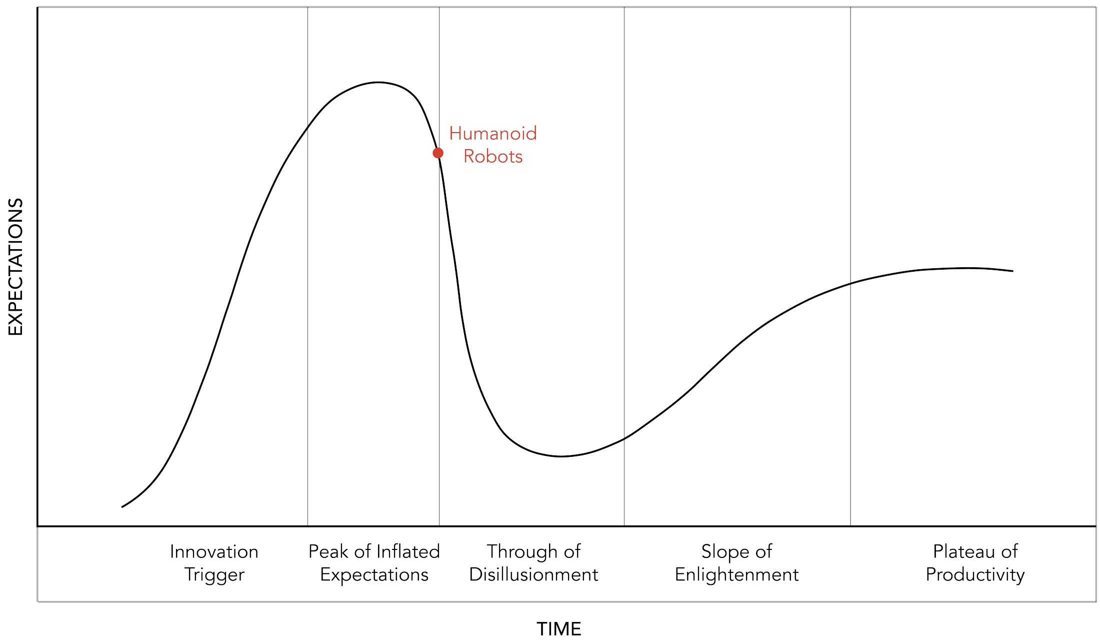

Figure 6.2: The illustration is adopted from Gartner (2024) and shows the estimated position of humanoid robots within the Gartner Hype Cycle.

The interviews indicate that humanoid robots are associated with high expectations, particularly in terms of increased productivity, improved safety and the ability to address labor shortages. These expectations align with broader robotics literature, which highlights potential gains from automation in construction environments, especially in relation to productivity and risk reduction (Bock, 2015; Khan et al., 2025; McKinsey Global Institute, 2017). At the same time, there is clear hesitation regarding implementation, including concerns about cost, technological maturity and integration into existing construction processes. These barriers are consistent with prior research identifying economic feasibility and system integration as key challenges for construction robotics (Odugu et al., 2025; Tafazzoli et al., 2024; Tulke et al., 2025). This combination of optimism and uncertainty suggests that humanoid robots are currently positioned between the "Peak of Inflated Expectations" and the

"Trough of Disillusionment" in the Gartner Hype Cycle (Gartner, 2024).

This position is further reinforced by the characteristics of the construction industry. As described in the literature by Koskela (2000) and Oesterreich and Teuteberg (2016), construction is a fragmented, project-based and risk-averse industry with low standardization compared to manufacturing sectors. This structural context reduces the speed of technology diffusion and explains why digital and robotic innovations often experience slower adoption curves than initially expected (Bock, 2015; McKinsey Global Institute, 2017).

A clearer understanding of this position can be achieved by comparing humanoid robots with task-specific robots. Task-specific robots have already reached a more mature stage of implementation in controlled or semi-controlled environments, such as drilling, layout and prefabrication tasks (Hilti, n.d.; Kromoser & Reichenbach, 2021; Xu et al., 2021). These systems align more closely with current BIM capabilities and structured workflows, which makes them more compatible with existing construction processes (Kim et al., 2021; Kim & Peavy, 2022). As a result, they are perceived as more predictable and practically feasible, which places them further along the Hype Cycle closer to early productivity adoption (Odugu et al., 2025). In contrast, humanoid robots are intended to operate in highly dynamic and unstructured environments, which increases requirements on perception, decision-making and information integration. The literature highlights that such systems depend heavily on high-quality, machine-readable BIM data and real-time environmental understanding (Roychoudhury et al., 2023; Wang et al., 2024; Zhu et al., 2025). These requirements are not yet fully met in current construction practice, which contributes to uncertainty regarding their feasibility. As shown in both the literature and the interviews, this mismatch between system requirements and industry readiness is a key factor explaining their current position in the Hype Cycle (Odugu et al., 2025; Sacks et al., 2020).

The case study reinforces this interpretation by illustrating the gap between perceived potential and actual feasibility. While humanoid robots are often discussed as a promising solution, the analyzed task shows that current BIM models, processes and project conditions are not yet sufficiently structured to support robotic execution. This reflects the broader literature on BIM-driven robotics, which emphasizes that successful implementation depends on alignment between digital models, process structures and site conditions (Kim & Peavy, 2022; Wang et al., 2024).

The findings indicate that the current position in the Hype Cycle is not fixed. The literature, interviews and case study suggest that adoption is constrained not only by technological maturity, but also by the readiness of the construction system itself. As developments in AI, perception and digital twin technologies continue, robots may become better at handling uncertainty and incomplete information (Chen et al., 2025; Jiang et al., 2022). This could gradually reduce the dependency on highly detailed BIM models and structured input data, potentially lowering system-level requirements for implementation. Such developments may influence how quickly humanoid robots move through the Hype Cycle towards more stable productivity-oriented adoption (Gartner, 2024).

6.5 Ethical Implications

The implementation of humanoid robots in construction raises several ethical and sustainability-related considerations related to work, safety, responsibility and the nature of construction practice itself. From the literature on construction robotics and BIM-based automation, it is clear that the feasibility of such systems depends not only on technological capability, but also on the structure and predictability of construction environments (Bock, 2015; Odugu et al., 2025; Wang et al., 2024). While many of these concerns are commonly discussed in relation to automation in general, both the literature and the empirical findings indicate that the characteristics of construction environments introduce additional complexity. As explained by Koskela (2000), construction sites are dynamic, unpredictable and highly dependent on human judgement, which creates challenges when introducing autonomous or semi-autonomous robotic systems. This was also reflected in the case application, where several construction activities relied on situational adaptations and experience-based decision-making that would be difficult to translate into standardized robotic workflows.

One concern emphasized in the interviews is the potential impact on employment and traditional construction roles. The introduction of humanoid robots may reduce the need for certain manual tasks, raising concerns regarding job displacement, changing competence requirements and employment security. These concerns align with findings in construction automation research conducted by Bock (2015) and Villani et al. (2018), which suggests that robotics tends to shift rather than eliminate labor demand, moving work towards planning, supervision and system coordination. From a sustainability perspective, this indicates a transition in social sustainability rather than a simple reduction of workforce, where new competencies related to digital tools and BIM-based workflows become increasingly important according to Kim and Peavy (2022). At the same time, both the literature and the interviews emphasize that humanoid robots could improve worker safety by reducing physically demanding, repetitive and hazardous tasks. This is one of the most consistently reported benefits of construction automation and is closely linked to occupational safety improvements in construction robotics research (Kang et al., 2024; Villani et al., 2018). Rather than completely replacing workers, the findings suggest that humanoid robots are more likely to transform construction roles by taking over repetitive and physically demanding activities, while humans remain responsible for tasks that require contextual understanding, adaptability and creative decision-making. This also has sustainability implications in terms of improving working conditions and reducing exposure to high-risk environments.

Another ethical dimension identified in the interviews concerns risks related to human–robot interaction and decision-making in uncertain environments. Several interviewees expressed uncertainty regarding how humanoid robots would behave in unpredictable construction scenarios, where unexpected events and situational adaptations occur frequently. This relates closely to the construction characteristics discussed in Section 2.4.1, where variability and continuous on-site decision-making are described as central aspects of construction practice by Koskela (2000). If a humanoid robot makes an incorrect decision, the consequences could involve safety risks, material damage or project delays. This raises questions regarding trust, accountability and responsibility in AI-driven systems, which are also highlighted in regulatory discussions on AI in safety-critical applications (European Parliament, 2024).

Closely related to this is the issue of decision autonomy. The findings indicate that the degree of autonomy granted to humanoid robots directly influences both perceived safety and ethical responsibility. While fully autonomous systems may increase efficiency, they may also reduce human oversight and make responsibility more difficult to define. Semi-autonomous or human-assisted systems were therefore generally perceived as more realistic in the near term, since they maintain a higher level of human control. This aligns with research by Raessa et al. (2020), which emphasizes the importance of human-in-the-loop control in uncertain environments (Raessa et al., 2020). This suggests that maintaining meaningful human supervision may be necessary not only from a technical perspective, but also to ensure accountability and trust in safety-critical construction environments.

The findings also highlight ethical concerns related to data collection and surveillance. As described in the literature, humanoid robots depend on sensing technologies such as cameras and LiDAR systems to perceive and navigate construction environments. However, continuous environmental scanning and data collection may create concerns regarding worker privacy and monitoring. Ethical implementation therefore requires transparent policies governing data collection, storage and access rights. Establishing trust in robotic systems may consequently depend not only on technical performance, but also on how responsibly collected data is managed within construction projects.

The findings also highlight ethical concerns related to data collection and surveillance. As described by Chen et al. (2025), humanoid robots depend on sensing technologies such as cameras and LiDAR systems to perceive and navigate construction environments. However, continuous environmental scanning and data collection may create concerns regarding worker privacy and monitoring. From a sustainability perspective, this introduces a need for responsible data governance, where transparency regarding data use, storage and access becomes essential for socially acceptable implementation of robotic systems (Sacks et al., 2020).

6.6 System Perspective on Implementation

The overall findings of this study show that for humanoid robots to function successfully in construction, multiple system components must be aligned. Implementation depends not only on technological capabilities, but also on how BIM, processes and organizational structures support robotic operation. The interdependence between digital information, construction processes and robotic execution is also emphasized in literature by Odugu et al. (2025) and Wang et al. (2024).

From a technological and process-related perspective, literature shows that robotic systems rely on structured and detailed information to perform tasks, as well as clearly defined sequences and constraints (Kim & Peavy, 2022; Zhu et al., 2025). This is clearly illustrated in the case study, where the BIM model lacks geometric detail, installation logic and production-related data required for robotic execution, while the work preparation process relies on verbal communication and on-site decision-making. This reflects how current construction practices are adapted for human flexibility instead of machine execution. For BIM models to support robotic systems, they would therefore need to evolve towards including component-level detail, predefined sequences and machine-readable production data, while construction processes would need to become more standardized and integrated with digital planning systems.

From an organizational perspective, the case study highlights that responsibilities are fragmented across actors when it comes to planning, execution and data management. While it is technically possible to increase the level of detail and structure within BIM models, this introduces a fundamental challenge related to responsibility. It remains unclear who within the construction process would be responsible for generating, structuring and maintaining the required data. In the case study, production-related decisions are largely handled by contractors on site and this means that the information required for robotic execution is neither centrally defined nor formally documented. Increasing the level of detail would therefore require additional time, resources and competencies, raising questions about whether this responsibility should lie with designers, BIM coordinators or production teams. This implies that the implementation of robotic systems requires clearer ownership of digital information, as well as new roles related to data management, system coordination and robotic operation, which aligns with previous studies by Karimi and Iordanova (2021) and Oesterreich and Teuteberg (2016) highlighting the importance of information governance and cross-disciplinary coordination in BIM-enabled automation.

These challenges are further reinforced by the physical conditions of construction sites. Even in the relatively organized case project, variability related to installations and spatial constraints requires continuous adaptation. This suggests that robotic implementation would require more controlled and predictable environments. The literature further emphasizes that such environments need to be supported by real-time data and sensing technologies to manage deviations and ensure alignment between the digital model and the physical site (Jiang et al., 2022; Sacks et al., 2020; Wang et al., 2024). This creates a fundamental tension in the implementation of humanoid robots in construction, where either robotic systems must become increasingly adaptive to uncertain environments, or construction processes themselves must become more standardized, structured and digitally controlled.

An important insight from this study is that these four aspects are strongly interdependent. Improvements in one area are not sufficient if others are not developed simultaneously. This system perspective explains why humanoid robots remain difficult to implement today, as the construction system is not yet aligned with the requirements imposed by higher levels of automation and robotic technologies.

7 Conclusions

The findings of this thesis show that the integration of humanoid robots in construction requires significant changes across technical, informational, process-related and organizational dimensions. A central result is that increased formalization and structuring of both digital information and construction processes is necessary to enable machine interpretation and execution. In particular, the alignment between BIM models, work preparation and on-site execution emerges as a critical requirement for robotic implementation.

Based on these findings, the following section provides direct answers to the research questions. It also highlights the main contributions of the study.

- What technical capabilities do humanoid robots require to operate on construction sites?

  Humanoid robots operating in construction environments require advanced perception, localization and navigation capabilities to interpret and move within highly unstructured and dynamic settings. In addition, robust task planning, manipulation and decision-making abilities are necessary to enable accurate and efficient execution of construction activities. Safety-critical functionalities, such as force limitation, collision detection and emergency stop mechanisms, are essential to ensure safe human-robot interaction on site.

- What types of information and modeling structures must be incorporated into BIM models to enable their use in robotic construction processes?

  BIM must provide structured, detailed and machine-readable data to support robotic execution. This includes high geometric granularity, unambiguous object definitions and enriched semantic and task-related information. Such information should be sufficiently formalized to enable automated interpretation for planning, coordination and execution of construction tasks by robotic systems.

- How must current construction workflows adapt to enable the integration of humanoid robots?

  The integration of humanoid robots requires a shift towards highly standardized and preplanned construction workflows. Production planning methods such as takt planning become essential to ensure predictability and coordination of robotic operations. Furthermore, implicit domain knowledge and ad-hoc decision-making must be formalized, structured and digitally represented to enable consistent robotic execution.

- How must organizational structures, competencies and responsibilities evolve within a construction company to enable humanoid robot adoption?

  Construction organizations must develop new roles and competencies related to the deployment and supervision of humanoid robotic systems. This transformation affects organizational structures by increasing the need for interdisciplinary collaboration between digital engineering, production planning and on-site operations. Additionally, robust data management capabilities are required to ensure consistent handling, updating and governance of the digital information supporting robotic execution.

These findings together show that the requirements across technical, informational, process and organizational dimensions are strongly interdependent. Improvements are most successful when implemented across the entire construction system including both physical and organizational aspects. The answers to these research questions collectively contribute to the overarching research question: *What requirements must construction sites, BIM modeling approaches and organizational processes fulfill to enable the integration of humanoid robots in construction?*

The study contributes to a structured identification of the changes required to enable the implementation of humanoid robots and other automated systems in the construction industry, particularly in relation to technical capabilities, BIM-based information structures, construction workflows and organizational adaptations.

Building on these findings, several directions for future research can be identified. A key priority is empirical validation of the proposed requirements through real-world pilot projects or experimental testbeds, which would help bridge the gap between conceptual frameworks and practical implementation on construction sites. In addition, the interaction between humans and humanoid robots in construction environments needs further investigation, particularly in relation to safety, trust, task allocation and adaptive collaboration under dynamic site conditions. Finally, future work could explore organizational transformation pathways in greater depth, including how companies can gradually transition towards robot-integrated production systems without disrupting ongoing construction operations.

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A
Interview Guide for Construction Companies

Background and current practice

- Could you briefly describe your role and how you work with innovation and automation within the organization?

- How do you currently use automation or robots in your projects, and how do you view the development of this trend in the construction industry in general?

Robots and construction processes

- What types of construction tasks do you think are best suited for automation or for being performed by robots?

- If you think of it in terms of different levels of robotic capabilities, what types of tasks do you think are suited for simpler robots compared to more advanced ones?

Humanoid robots

- In what situations or work tasks do you think humanoid robots could be useful on a construction site?

- What do you see as the biggest obstacles to using such robots in construction today, for example technical, organizational or financial?

Physical requirements at the construction site

- How do you think the construction site or on-site work methods would need to change to allow robots to work there more efficiently?

BIM and information requirements

- If robots were to perform work based on digital models, how do you think issues related to liability and legal matters would need to be addressed?

- Do you think the BIM model would need to be legally binding?

Organization and future

- How do you think work methods, project organization or competencies within construction companies would need to change if robots become more common?

- What is your view on the future of robotization in the construction industry? Do you think this development will occur gradually or through major changes?

B

Interview Guide for Robotics Companies

Background and current practice

- Could you describe your role and how you work with robotics or automation?

- What types of robotic systems are your company currently developing or working with, and how do you see the development of robotics in the construction industry?

Robotics and construction tasks

- What types of construction tasks are currently most suitable for robotic systems?

- If you consider different levels of robotic capabilities, how would you distinguish between simpler robotic systems and more advanced ones in terms of what they can do?

Humanoid robots

- In what situations or types of tasks do you think humanoid robots could be relevant in construction?

- What do you see as the main challenges for implementing such systems today?

Technical and environmental requirements

- What are the main technical or environmental requirements for robots to operate effectively on construction sites?

- How do current construction environments limit robotic performance?

BIM and information requirements

- How is BIM or digital model data used in relation to robotic systems today?

- What requirements do robotic systems place on the structure and level of detail of BIM data?

- Could you describe how information flows from the BIM model to the robot in practice, including any tools, software, or data formats used?

Organization and future

- How do you think construction processes or project organizations need to change to support increased use of robotics?

- How do you see the future development of robotics in construction, and what role will BIM play in this process?

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