Construction Robotics (2023) 7:89–103
https://doi.org/10.1007/s41693-023-00098-3

ORIGINAL PAPER

Cobot uptake in construction: embedding collaborative robots in digital construction processes

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Received: 16 December 2022 / Accepted: 3 April 2023 / Published online: 20 April 2023

Abstract
The paper at hand investigates the interrelation of automation and collaboration in digital construction processes. Labor shortage, demographic change, and a deficit in productivity motivate automation in construction. While the automation of single tasks is on its way, there is a lack of collaboration between automated equipment and robots along the digital construction process. To foster the development of collaborating robots, definitions and classification criteria for automation and collaboration activities are given. With these criteria at hand, it is possible to classify scientific examples from literature. On top of that, the paper introduces a prototyping framework for automated and collaborative equipment. The framework is thoroughly tested in an earthworks case study consisting of automated and collaborative excavation and compacting of an area. Through the collaboration of an automated excavator and vibratory plate, it is possible to simultaneously execute the 'excavation' and 'compaction' task, speeding up the overall earthworks process by a factor of almost two. Along with a higher productivity, the high degree of automation allows for safer work, as less workers are exposed to dangerous workspaces and the quality increases through continuous quality checking and integrated documentation of as-built data in BIM models.

Keywords Cobots · BIM · Digital twin · Construction process · Collaboration · Automation

1 Introduction

As 35% of German construction companies reported problems finding skilled workers (ifo Institute 2021), increasing automation on construction sites becomes a target of high priority. The prevailing demographic change in many countries aggregates labor shortages and the need to increase automation efforts (Bundesministerium des Inneren 2011). On top of that, a higher level of automation positively affects closing the gap in productivity between the overall economy (60% increase of gross value added per hour worked since 1995) and the construction industry (20%) (McKinsey and Company 2017). Currently, construction automation activities can be observed in two main fields: digital construction processes and automated equipment.

Regarding digital construction processes, BIM (Building Information Modeling) has become increasingly important in recent years (Spengler and Peter 2020). The digital model of a building is at the center of BIM. This contains both three-dimensional geometric information and non-geometrical information such as materials, costs, and technical properties, and is, therefore, characterized by a high level of information depth (Borrmann et al. 2015). The vision for BIM is to become amultidimensional digital twin, containing all necessary information on objects and processes for their entire lifecycles and all stakeholders (Trauer et al. 2020; Khajavi et al. 2019).

Focusing on automated equipment, two major trends are observable. On the one hand, there is the automation of conventional heavy equipment, mainly based on assistance systems, e.g., collision detection systems (Engineering 2022) or retrofitting, e.g., machine control systems (Topcon 2022). On the other hand, newly developed products with a high level of automation are progressively introduced into the market. Frequently, they are based on completely new equipment and process handling concepts transferred over from robotic manufacturers or other industry domains, e.g.,

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overhead drilling robots (Xu et al. 2022). Most of these newly introduced equipment types can be classified as single-task construction robots (Bock and Linner 2016).

For future construction automation activities, automated equipment is to be integrated with digital construction processes so that efficiency potentials can be exploited and new business models can be developed. To achieve these benefits, collaboration of equipment along the construction process has to be established. This will enable construction equipment to become increasingly integrated into the construction value chain, reducing costs and increasing safety and efficiency (Terol 2020).

While the integration of individual equipment is fully underway for newly developed construction robot concepts and heavy earthmoving machines (see Sect. 2.2), cross-task collaboration along the construction process (e.g., light construction equipment with an operating weight below 1.5 metric tons (Ammann Group 2022; GmbH 2022)), is excluded from this development, inhibiting the potential for additional safety, efficiency, and cost reduction (Geosystems 2021; Benko 2022).

Therefore, the object of this paper is to investigate the embedding of collaborative, automated equipment in digital construction processes, specifically by depicting the overlap of automation and collaboration (Sect. 2). Additionally, the current state of science regarding the level of automation and collaboration within the construction industry is classified (3). Introducing a conceptual framework for the joint automation of the digital construction process and the corresponding equipment (4), the paper finishes by conducting a case study on an exemplary collaborative earthwork process to evaluate the framework (5).

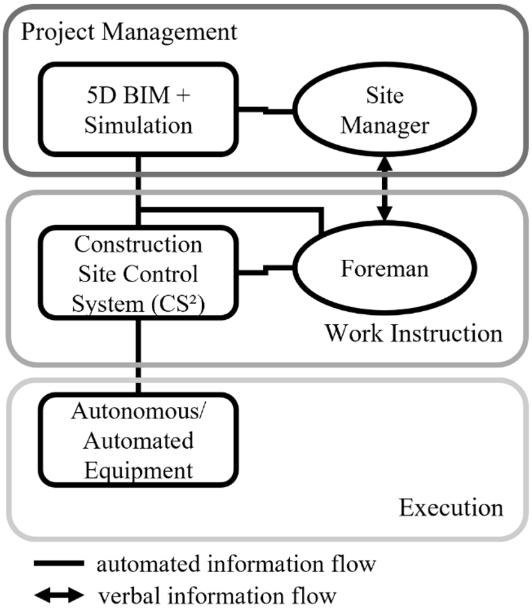


Fig. 1 Task management ecosystem on construction sites (Schöberl et al. 2021)

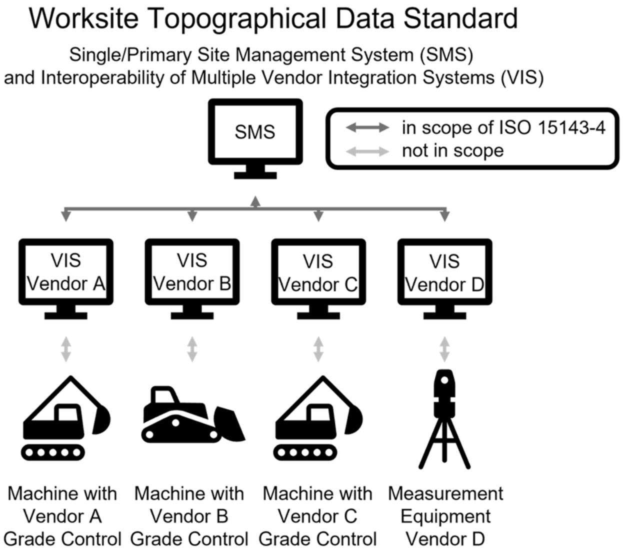


Fig. 2 Structure of topographical data exchange on construction sites according to ISO 15143-4 (Costlow 2020)

2 Fundamentals

With ongoing digitalization efforts, the digital construction site becomes more complex. It is, therefore, useful to depict the construction site management structure before diving deeper into its components, the digital construction process, and automated equipment. Generally, tasks on a construction site pass through three stages: project management, work instruction, and execution (Schöberl et al. 2021). Depending on the type of construction (building or infrastructure), project management revolves around either a BIM (e.g., *.ifc) or digital terrain (e.g., Land*.xml) model that is enhanced through multiple dimensions (5D) and simulations (Fischer et al. 2021). Between project management and the actual execution on site, the respective information model must be transformed through a Construction Site Control System (CS^2) at the work instruction level to form an executable task. The task is executed by semi-automated heavy equipment such as machine-controlled excavators or autonomous robots. Figure 1 depicts the digital task management on future construction sites.

A similar three-level structure is part of the ISO 15143-4, a norm currently under development, focusing on topographical data exchange on mixed fleet worksites (Costlow 2020). It standardizes the server-to-server data exchange between machine-specific Vendor Integration Systems (VIS), more commonly known as grade- or machine control systems, and a general Site Management System (SMS) containing overall jobsite information and digital terrain models, as shown in Fig. 2.

The SMS, 5D BIM, and CS^2 incorporate digital construction processes, while autonomous/automated equipment and machines with grade control incorporate automated equipment. As these two main fields of construction site automation are integral to this contribution, they are further elaborated upon in the following sections.

2.1 Digital construction process

In the context of this work, Building Information Modeling (BIM) is defined as the "use of a shared digital representation of a built asset to facilitate design, construction, and operation processes to form a reliable basis for decisions" (International Standardization Organization 2018). The aforementioned information models (*.ifc and Land*.xml) comply with this definition. A BIM model is an object-oriented representation of a building, whereas a digital terrain model (DTM) is a digital representation by means of a point cloud and a polygon mesh of existing or planned topographies.

2.2 Automated equipment

To interact with these digital representations, automated equipment and robots must be able to align themselves with the information model in the digital environment. Therefore, automated equipment in open-field infrastructure construction uses positioning systems such as differential global navigation satellite system (DGNSS) or real-time kinematics (RTK) (Mallela et al. 2018; Persson 2018), while autonomous robots or more automated equipment in building construction use localization algorithms such as simultaneous localization and mapping (SLAM) (Immonen et al. 2021; Fraunhofer Institute of Optronics 2022) or ultra-wideband (UWB) (Vahdatikhaki et al. 2015).

Construction equipment can be classified by weight or purpose. Purpose categories can be found in the Baugeraeteliste (BGL) (König 2014) or the ISO standard ISO/TR 12603:2010 (2010). The operating weight thresholds are 1.5 metric tons for light to compact equipment and 10 metric tons for compact to heavy construction equipment (Kubota 2022; Bobcat 2022). Light equipment includes mostly handheld and non-ride-on equipment. Most of the newly developed construction robot concepts fall under the light equipment operating weight threshold. Application (industry, service, construction, etc.) or abilities (autonomous mobile, humanoid, cobot, etc.) are the decisive criteria for robot classification (Institute of Electrical and Electronics Engineers (IEEE) 2022). A rigorous classification by ability is only possible if the classes are defined accordingly. While there is a straightforward definition for the ability of a robot to assist humans (automated/autonomous) with the six levels of automation (LOA) defined by the Society of Automotive Engineers (SAE, see Fig. 3) (SAE International 2021) or the six levels of construction robot autonomy (see Fig. 4) (Liang et al. 2021), the term collaboration is only loosely defined. This leads to the fact that currently the main feature of differentiation between cobots and industrial robots is the ability of the former to be able to work safely alongside humans (Zaatari et al. 2019). However, other authors, like Sadik and Urban (Sadik and Urban 2017), see collaborative robotics as an entirely new branch of industrial robotics, indicating a collaboration not limited to human–robot interaction and empowering the idea of cooperative manufacturing among completely automated process chains.

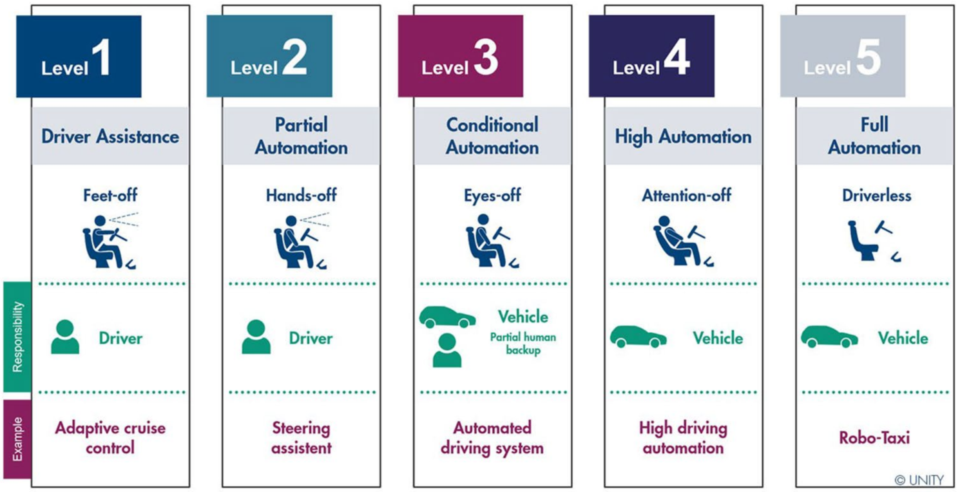


Fig. 3 Level of vehicle automation based on SAE J3016 (Unity 2019)

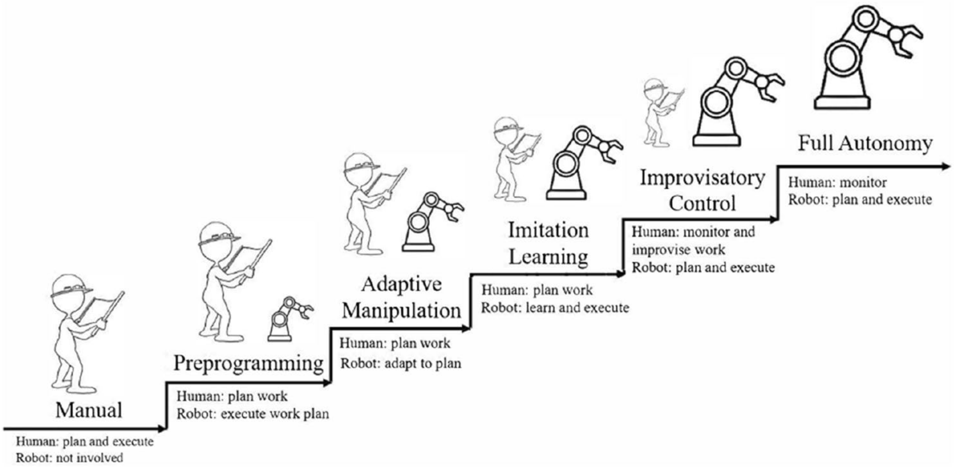
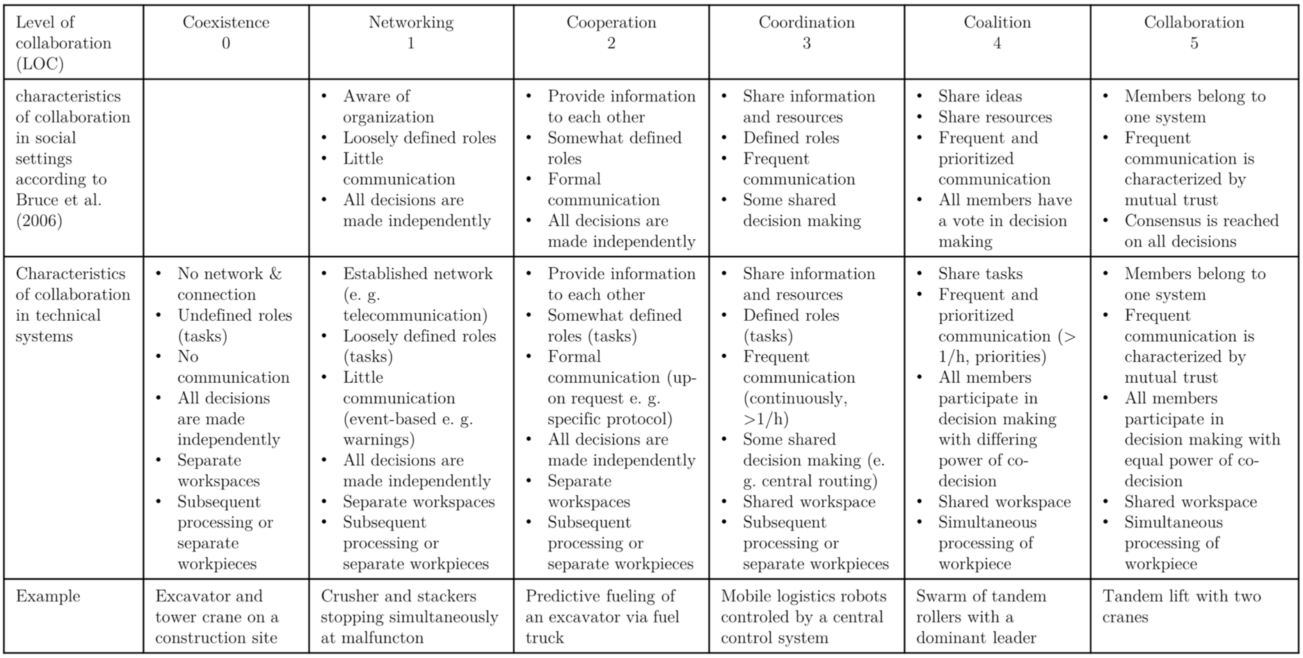


Fig. 4 Levels of construction robot automation based on Liang et al. (2021)

2.3 Cross-task collaboration

While levels of automation mainly deal with whether a human, a robot, or some other piece of equipment handles a task, i.e., the allocation of different tasks within a process, there is no measure of cross-task collaboration between different actors with these being either robots, machines, or humans. Being able to introduce collaborating robots and foster widespread adoption of robots on construction sites requires a unified and comprehensive framework for cross-task collaboration, similar to the levels of automation.

Non-technical sectors, especially in the social sciences, have clearly defined collaboration criterion and related terms. According to Frey et al. (2006), who compared various stage models of collaboration, it can be defined as a “cooperative way that two or more entities work together toward a shared goal”. They further propose five levels of collaboration (LOC) and their characteristics, as seen in Fig. 5. These social characteristics constitute the basis of the collaboration framework of this paper and are adapted to fit into the technical context of robotics. On top of merely appropriating the characteristics proposed by Frey



Level of collaboration (LOC)	Coexistence 0	Networking 1	Cooperation 2	Coordination 3	Coalition 4	Collaboration 5
characteristics of collaboration in social settings according to Bruce et al. (2006)		• Aware of organization • Loosely defined roles • Little communication • All decisions are made independently	• Provide information to each other • Somewhat defined roles • Formal communication • All decisions are made independently	• Share information and resources • Defined roles • Frequent communication • Some shared decision making	• Share ideas • Share resources • Frequent and prioritized communication • All members have a vote in decision making	• Members belong to one system • Frequent communication is characterized by mutual trust • Consensus is reached on all decisions
Characteristics of collaboration in technical systems	• No network & connection • Undefined roles (tasks) • No communication • All decisions are made independently • Separate workspaces • Subsequent processing or separate workpieces	• Established network (e. g. telecommunication) • Loosely defined roles (tasks) • Little communication (event-based e. g. warnings) • All decisions are made independently • Separate workspaces • Subsequent processing or separate workpieces	• Provide information to each other • Somewhat defined roles (tasks) • Formal communication (up-on request e. g. specific protocol) • All decisions are made independently • Separate workspaces • Subsequent processing or separate workpieces	• Share information and resources • Defined roles (tasks) • Frequent communication (continuously, >1/h) • Some shared decision making (e. g. central routing) • Shared workspace • Subsequent processing or separate workpieces	• Share tasks • Frequent and prioritized communication (> 1/h, priorities) • All members participate in decision making with differing power of co-decision • Shared workspace • Simultaneous processing of workpiece	• Members belong to one system • Frequent communication is characterized by mutual trust • All members participate in decision making with equal power of co-decision • Shared workspace • Simultaneous processing of workpiece
Example	Excavator and tower crane on a construction site	Crusher and stackers stopping simultaneously at malfuncton	Predictive fueling of an excavator via fuel truck	Mobile logistics robots controled by a central control system	Swarm of tandem rollers with a dominant leader	Tandem lift with two cranes

Fig. 5 Level of collaboration in social (Frey et al. 2006) and technical systems with exemplary construction processes

et al., two new characteristics (workspace and workpieces) are introduced. To foster an understanding of the characteristics, an example of a construction process is given for each level of collaboration.

3 State of science

The state of science continues the refinement of cross-task collaboration, by giving further examples for construction processes executed by collaborating robots or equipment. The examples are depicted in the automation–collaboration matrix in Fig. 6 and will be briefly explained in the following.

3.1 Cross-task collaboration examples

Exemplary processes for coexistence (LOC 0) are the autonomous wheel loader supported by a 3D graphical job tool of Halbach and Halme (2013) (LOA 1) and on the other end of the LOA-scale, the autonomous excavator platform by Heikkilae et al. (2019) (LOA 5). In between are the service robot with mobile platform and manipulator (Fottner et al. 2021) and the rebar tying robot Tybot (Brosque 2022) (LOA 2). As well as an automated material hauling robot by safeAI (Brosque 2022) (LOA 3) and an autonomous excavating unit (Zhao and Zhang 2021) (LOA 4) similar to Built Robotics add-on (Robotics 2022).

The networking level (LOC 1) consists of robots concerned with creating a communication network, the intelligent robot communication map by Im et al. (2014) (LOA 4). Xu et al. (2021) and Brosque et al. (2021) focus on a robotic system for overhead drilling, the Jaibot (LOA 2). Automated scaffolding is the aim of KEWAZO in a case study with Bechtle (Brosque 2022) (LOA 1).

Use cases with cooperating robots (LOC 2) are found with Yamamoto et. al.'s hydraulic excavator autonomously loading a dump truck (Yamamoto et al. 2009) (LOA 4) and Follini et al.'s (2020, 2022) mobile robotic platforms (LOA 3). Two teleoperated concepts are Wallace et al. (2020) with their virtual teleoperation framework for multiple robots (LOA 1) and Dadhich et al. (2016) with their assisted tele-remote operation of a wheel loader loading a dumper (LOA 2).

Coordinated robots (LOC 3) are fleets of order picking robots controlled by a central control system, like magazino's toru (Fottner et al. 2021) (LOA 3), human and robotic workers in vehicle assembly (Conti et al. 2020), map-exploring robots (Quattrini Li et al. 2020) (LOA 4), and unmanned aerial vehicles (UAVs) with centralized task assignment (Poudel and Moh 2022) (LOA 5).

Coalitions of robots (LOC 4) work in assisted road compaction (Bouvet et al. 2001) (LOA 1) and automated compaction with tandem rollers (Ropertz et al. 2018) (LOA 4). Inspecting tunnels can be simplified with a multi-robot system created by Miura et al. (2016) (LOA 5).

Finally, collaboration (LOC 5) on a manual level of automation (LOA 0) is seen in tandem lifting operations of cranes (Kargar et al. 2022). More automated is the multi-robot system for environmental assessment (Nagatani et al. 2021) (LOA 2) and a swarm of UAVs with distributed, auction-based task assignment (Poudel and Moh 2022).

3.2 Classification and conclusion

The literature examples from the previous subsection validated the automation–collaboration matrix and the applicability of the characteristics of the respective level of collaboration. Furthermore, the four quadrants of the automation–collaboration matrix indicate four representative automation and collaboration scenarios.

Marking the four respective quadrants, a clear cut-off criterion can be established. In the case of the level of automation, shown on the *y*-axis, this cut-off is made at the point at which the automated systems change from merely being of assistance to an operator to controlling the environment with human operators merely functioning as supervisors. This is

Fig. 6 Level of collaboration and level of automation for construction processes found in literature

LOA 5	Heikkilä (2019)			Poudel (2022)	Miura (2016)	Poudel (2022)
LOA 4	Zhao (2021)	Im (2014)	Yamamoto (2009)	Conti (2020) Li (2020)	Ropertz (2018)	
LOA 3	Brosque (2022)		Follini (2020)	Fottner (2021)		
LOA 2	Fottner (2021) Brosque (2022)	Xu (2021) Brosque (2021)	Dadhich (2016)			Nagatoni (2021)
LOA 1	Halbach (2013)	Brosque (2022)	Wallace (2020)		Bouvet (2001)	
LOA 0						Kargar (2022)
	LOC 0	LOC 1	LOC 2	LOC 3	LOC 4	LOC 5

in accordance with the distinction usually made by the levels of automation (SAE International 2021). For the *x*-axis, where the levels of collaboration are applied, this division is made at the point at which different process stakeholders share a common workspace and make decisions collaboratively, dependent upon one another. Using this classification, four distinctive categories can be deduced. The first one, located at the lower left side of the matrix includes tasks with little automation and collaboration, and is therefore named "Independent Manual Machines". To the right, tasks that are performed collaboratively but are still only barely automated represent "Manual Collaboration Heroes". Especially in current construction practices, an overwhelming majority of tasks fall into this category, although these kinds of processes are not addressed in scientific publications. This underlines the gap between current efforts to automate individual tasks and the need for the automation of real-world collaborative processes which this paper addresses. Moving to the upper left side of the matrix, "Independent Autonomous Robots", characterized by a high level of automation but very little collaboration constitute the third quadrant. Oftentimes a specialized robot performs a very specific task independently. This is a field frequently addressed in academia but of very little impact regarding efficiency gains since the process chain itself remains unchanged; if anything, the process becomes less collaborative. The goal when developing automation concepts for construction processes should be to position them in the upper right side of the matrix, where "Automated Collaboration Stars" are located. These are best described as all-encompassing automation approaches to a complete construction process chain. They not only reduce the amount of manual labor needed for an individual task but are able to automate entire processes which previously were dependent on human supervision and interaction.

Concluding the state of science, a critical discrepancy between current scientific efforts to automate individual tasks of the construction site and thereby inevitably increasing its process efficiency was illustrated. What is needed is a step-wise approach, focusing on interdependent and interconnected process chains. In the following sections, such an approach will first be derived theoretically and then implemented using a practical example of an earthworks process in the form of a case study (Fig. 7).

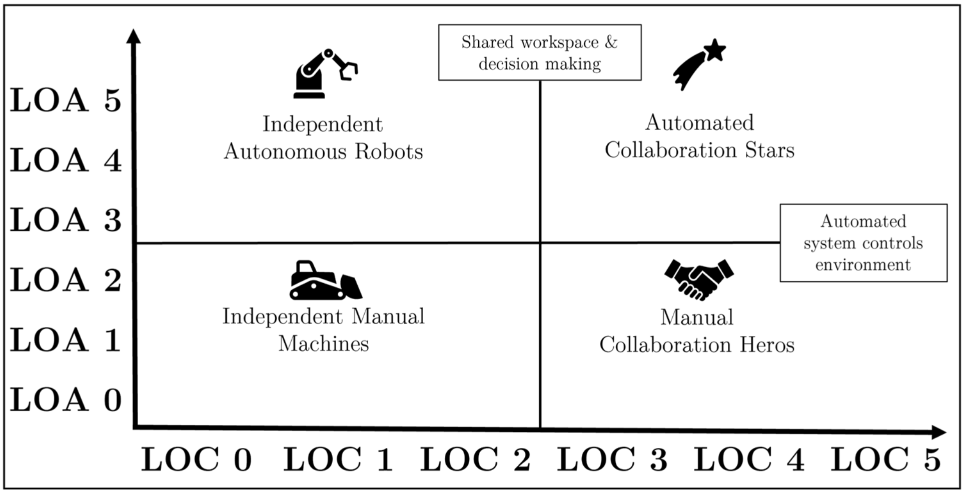
4 Prototyping framework

The dilemma of trying to introduce automation at the construction site and simultaneously risk undermining its need for collaboration is solved by introducing a prototyping framework (see Fig. 8).

Starting with a thorough process analysis of current construction processes using BPMN, the level of collaboration, as well as, at a later stage, the level of automation, can be deduced. Using information flows and the amount of interaction between different process stakeholders, any process can be analyzed in terms of its need for collaboration. Next up, a BIM integration concept allows necessary information of the digital construction process to be included or generated within an overarching digital model. It is crucial that the equipment is able to receive and transmit the information as well as incorporate it into its decision-making. After laying

Fig. 8 Three step prototyping framework for automated and collaborative construction processes

Fig. 7 Collaboration–automation matrix for construction sites



the theoretical groundwork of the process and ensuring that the quintessential digital model has been established, employing a step-wise approach to move up the automation–collaboration matrix is recommended. The following sections elaborate upon the theoretical groundwork, starting with a proposition of how to analyze the collaboration and automation potential of construction processes.

4.1 Process analysis

Analyzing the level of collaboration for a given process can be accomplished by conceptualizing it upfront using business process modeling techniques (Rosing 2015; Decker and Barros 2007). Business Process Model and Notation (BPMN) has been established as a standardized means of visualizing complex processes and workflows in various domains, among them the construction industry (Ali and Badinelli 2016). Depending on the level of granularity of the analysis, processes can be envisioned, evaluated, and improved upon (Makni et al. 2010). BPMN depicts process chains using events, tasks, and gateways. Starting off with an occurring event, a task that needs to be completed is triggered. It may be followed up by any amount of other tasks or events, depending on the process. A gateway marks a decision point, whereby two different events may occur or multiple events may occur simultaneously. Pools, commonly symbolized via big, all-encompassing boxes, house all events, tasks, and gateways. They stand for different process stakeholders and are subdivided into different swimlanes. In general, process stakeholders may be machines, humans, or even "Black Boxes". Information flow (dotted lines) and sequence flow (solid lines) connect all events, tasks, and gateways and conclude the basic methodological BPMN building blocks. (Rosing 2015)

Employing BPMN as a tool to understand business processes offers several advantages (Makni et al. 2010). The primary one in this context is being able to showcase the frequency of communication among different process stakeholders along the entire process chain. As the methodological framework of BPMN is initially indifferent to whether a process is executed by humans or machines (Richerzhagen and Fuchs 2021), outlining a process allows focusing primarily on the level of collaboration, neglecting the level of automation. Nonetheless, automation potential can be showcased as well, as task descriptions generally include by what means the task is currently accomplished. Figure 9 showcases an exemplary process model using BPMN methodology. Depending on the amount of interaction, that is, the amount of information flow between different lanes and pools (process stakeholders), the level of collaboration can be estimated at a single glance. In the process, an initial task, set off by a starting event, sends a message to another process stakeholder, thereby simultaneously starting a second task. Additionally, there is the potential of failure from the initial task, triggering an error warning and end event, which once again is communicated to the second process. If the message is not received, process number 2 moves on with another intermediate task, the result of which is essential for the main task of process 1, in this case manually accomplished. Using stored knowledge as well as the process information from process 2, process 1 moves on to the implementation, which automatically completes the process chain if not checked upon after a certain time. Process 2 finishes separately, giving a final update of its status to an operator instructed to check the successful completion of the entire process chain. Depending on the complexity and subtlety of the model (and the process itself), interactions between multiple lanes and pools may become increasingly convoluted. In

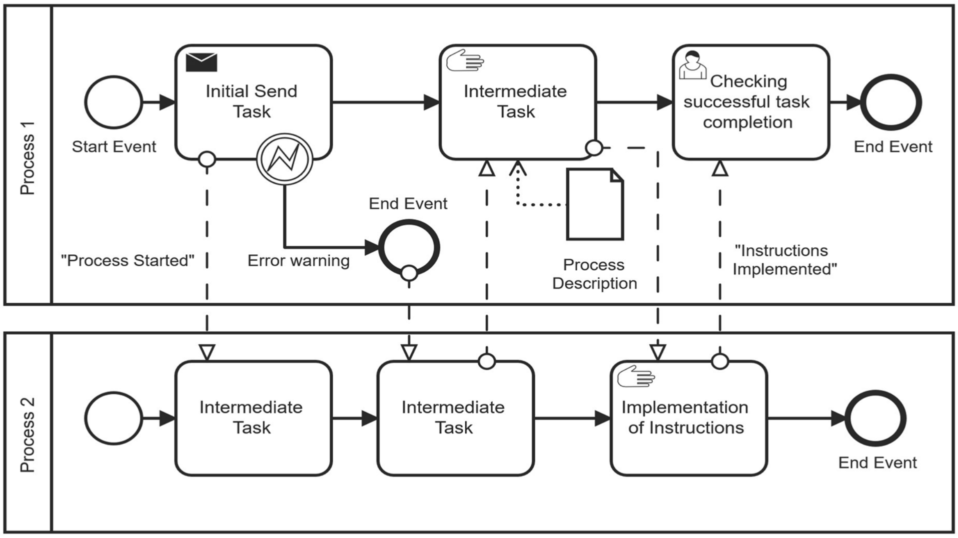


Fig. 9 Exemplary process model using BPMN

these cases, it is all the more essential to formulate a clear conceptual framework upfront to be able to deduce the level of collaboration, keep it constant throughout automation efforts, and to even increase it further while improving upon process efficiency. Conclusively, when determining the level of collaboration of virtually any process, especially with regard to complex and adaptive process chains, BPMN proves to be an invaluable tool, making it optimally suited to model digital construction processes.

4.2 Process integration

To integrate robots, respectively, equipment in this digital construction process, this subsection introduces a general BIM integration concept. The concept for integrating BIM and construction equipment comprises five essential steps and was originally introduced for light equipment (Schöberl et al. 2022).

1. First, the information necessary for the task must be included or generated in the information model. For this purpose, BIM or DTM software allows the user to check or edit the information model.
2. The information must then be exported from the information model, which can be done using the *.ifc or Land*.xml standard data formats. The focus of the thereby exported data has to lie on constricting the information flow to only relevant parameters for the construction equipment operation to keep data traffic as low as possible. Predefined specifications of the task must be obeyed to ensure that the meaning of the data is conserved.
3. To work with the aforementioned information, the equipment must be able to receive and transmit information from a technical standpoint. Since the movement of light equipment happens relatively unrestricted between different construction sites, a wireless network connection employing tele- or radio- communication is recommended. Narrowband IoT (NB-IoT) and Long-Term Evolution for Machine (LTE-Cat-M1) protocols were specifically developed for those kinds of applications (Ratasuk et al. 2016).
4. Data transformation capabilities within the equipment itself ensure adequate interpretation of the received, and the to-be transmitted, data. In addition to this, light equipment needs to be able to align itself with data generated within the operation, that is, the construction process, which is stored in the information model. Sensor systems alongside localization and object detection algorithms are able to provide the machine with these abilities.
5. First, data generated during operation from light equipment are transmitted to the information model. Second, the data are added to the overarching information model for documentation or progress tracking purposes. To do so, the information model must follow an adequate information structure. BIM files in the *.ifc-format are object oriented and allow information to be added to the respective objects. DTMs in the Land*.xml-format can either be updated (new file) or the information can be added to each geographical point. Another option for both information models is to include the information globally, e. g., in the file header.

4.3 Step-wise development

With these prerequisites installed, simultaneous development of level of automation and level of collaboration can be achieved in a step-wise development approach. In many cases, when taking a purely manual process as a base, enabling teleoperation of the equipment constitutes the first step of automation. However, this, in most cases, already leads to a reduction in information flow, as the human operator is no longer on site but works remotely, inhibiting informal information flow (Fisher et al. 2006). The second step then consists of implementing progressively more scenarios in which the equipment can steer autonomously at an ever-increasing degree of complexity until finally, the equipment is able to operate autonomously under almost any circumstances with very little human supervision. However, the flow of crucial information for other process stakeholders and the possibility of adapting the process in a collaborative manner are oftentimes significantly compromised, as the equipment no longer communicates as extensively with other process stakeholders as a human operator would and is additionally very dependent on the rigidity of its routine. Therefore, as a final step in the implementation of an automated collaborative solution, it is necessary to enable machinery to act jointly and interdependently with other machinery and humans alike, for shared workspaces and simultaneous processing of workpieces are integral to reaching true process efficiency (Ferreira and Antunes 2007). This includes the necessity for the automated solution to be adaptable to the needs of other process stakeholders or changing boundary conditions, distinctive for construction sites. In this regard, it is furthermore necessary to include each and every process member in an overarching decision-making process, creating opportunities for mutual trust to emerge. With the goal of all members belonging to one system, this can be done via enforcing frequent communication as well as spontaneous and consensual decision-making.

5 Case study

To validate the prototyping framework described in Sect. 4, an earthworks case study consisting of a vibratory plate as compaction equipment and an excavator is implemented as an example. The objective is to increase the LOA of the state-of-the-art process from 0 to 5, while keeping the LOC from the original process at 4 or above. This is achieved by following the prototyping framework introduced in the previous chapter and following a stepwise development approach.

5.1 Process analysis

Beginning the case study by looking at the process as it is accomplished according to state-of-the-art knowledge, an initial BPMN process model is developed. The focus of Fig. 10, therefore, lies on the visualization of information flows between every necessary process stakeholder, showcased via the BPMN methodology. This initial step is essential in later being able to implement these using an automated approach to information exchange.

Splitting up the process between three main stakeholders, the vibratory plate, an excavator, and a supervisor, an all-encompassing view of the process can be generated. Starting with the excavator preparing the ground for the plate to compact, the initial task ideally already sets off two information flows, one to (the operator handling) the plate, and the other to the supervisor of the construction site. As the plate waits for the excavator to finish its task, a timer is set. After receiving the message that the excavator has finished its tasks, the plate goes to work. To complete the compaction successfully, it is necessary for it to have access to predefined and measurable parameters. Once access is granted, an evaluation takes place, determining whether the result is satisfactory or not. The critical decision in this case is made by either a human operator, who navigated the plate beforehand or an automated compaction measurement system. For the proceeding process chain, the specific technical configuration does not matter. What matters from a process point of view is the fact that each respective result is communicated to the supervisor, whereas the only communication taking place between the plate and the excavator happens when the compaction is successfully completed. Thereafter, the excavator, again independent of whether this is done via a skilled operator or an automated system, also checks the area, verifying the successful completion of the task redundantly. If there happens to be more iterations or more instances needed, i.e., if there is more area to be modified, the process starts again. At the end of the process chain, a final examination of the result takes place, oftentimes complemented by expository measurements. This is usually carried out by a human operator, not necessarily the supervisor himself, but certainly someone dependent on his process parameter information.

Imagining the process being conducted by mainly human operators with a very low level of automation, as is the current state-of-the-art, a lot of information flow and interaction takes place between various process stakeholders. These

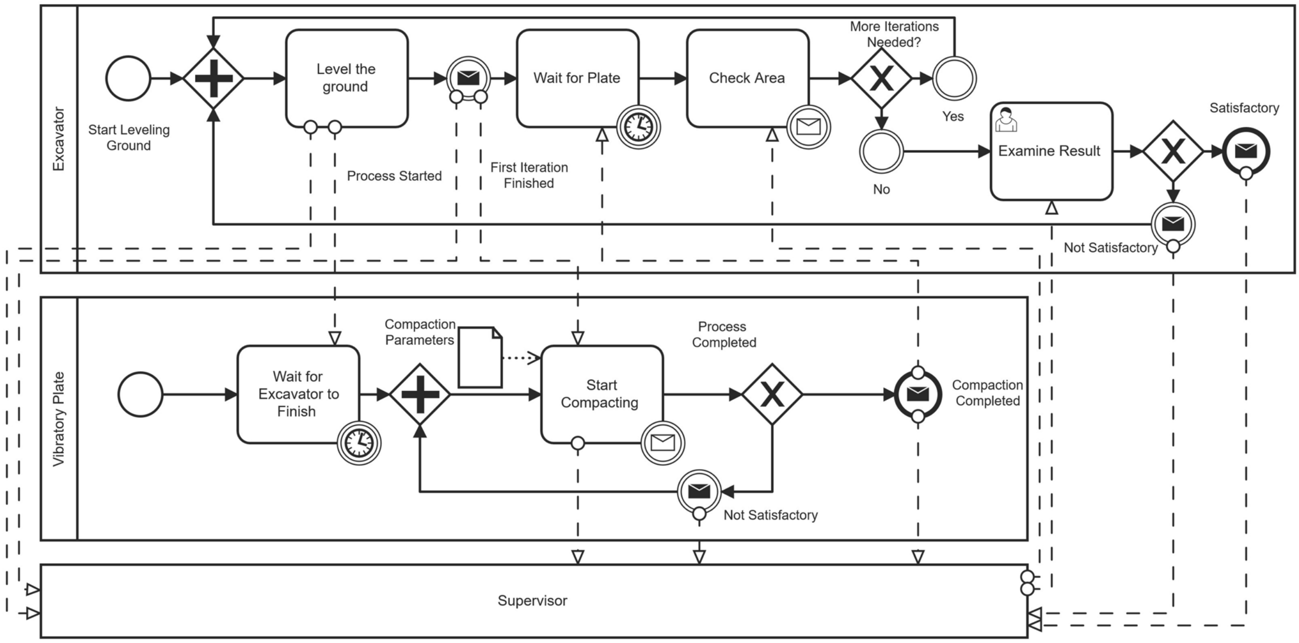


Fig. 10 Vibratory plate process model using BPMN

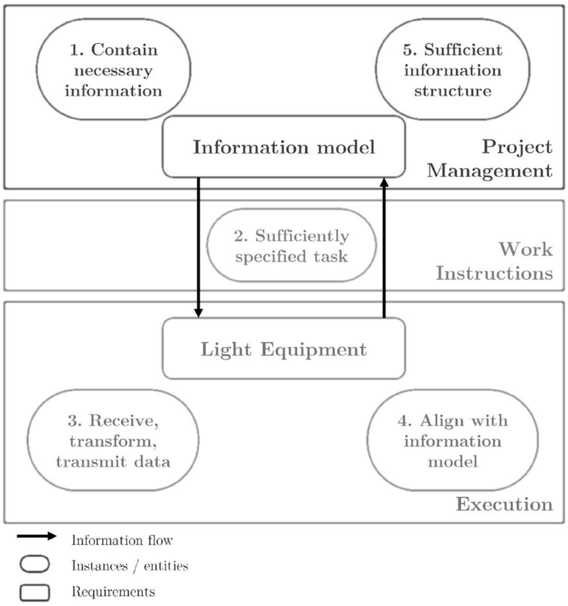


Fig. 11 BIM integration concept

flows are oftentimes verbal, but not limited to explicit and formalized communication. Again and again, little cues as to whether the excavator operator has finished his tasks or the supervisor nodding in agreement count as valuable information toward reaching the process goal (Fisher et al. 2006). The amount of interaction taking place among human operators cannot be underestimated, especially if the process happens to take place among actors with mutual trust. Therefore, automating individual parts of the process always risks undermining the level of collaboration and endangering efficiency gains by restricting information flows between different actors. Analyzing the process within the framework of the proposed automation–collaboration matrix, it can be located in the lower right quadrant, as it is currently characterized by a very high level of collaboration (same workspace, belonging to the same system, mutual trust) and a low level of automation (mainly manual tasks). Therefore, it is ideally suited for the case study, where the goal is to showcase that implementing an automated solution does not necessarily have to compromise the level of collaboration.

5.2 Process integration

To embed automated equipment in the depicted digital construction process, in accordance with Figs. 11, 12 shows the five necessary steps for the BIM integration of equipment. The information flows include the deployed data formats. The individual steps are described in detail below.

1. The first step in the realization of the case study was to create a digital terrain model of the construction area

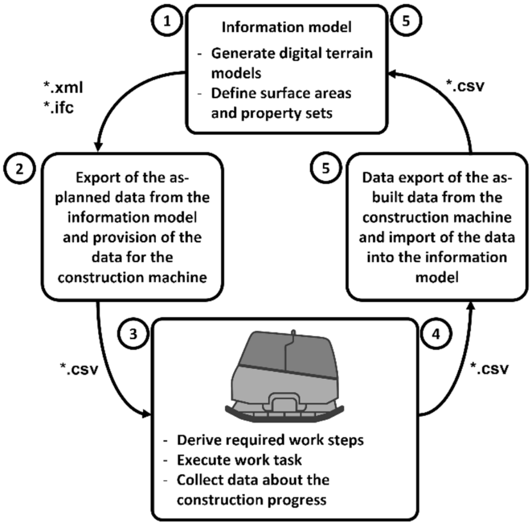


Fig. 12 BIM integration of the vibratory plate

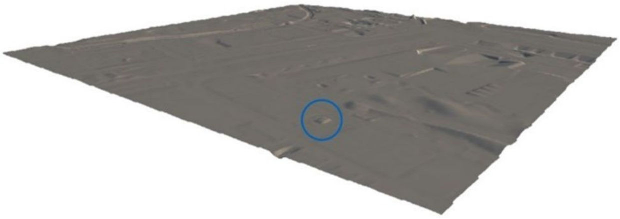
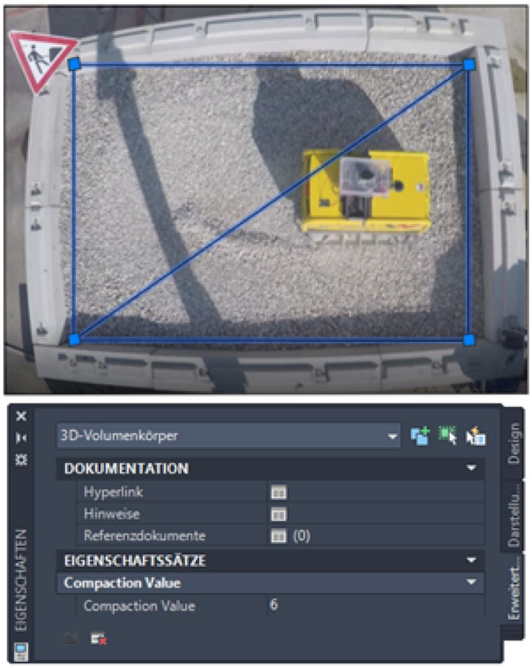


Fig. 13 Digital terrain model of the construction site



3D-Volumenkörper

DOKUMENTATION

Hyperlink

Hinweise

Referenzdokumente (0)

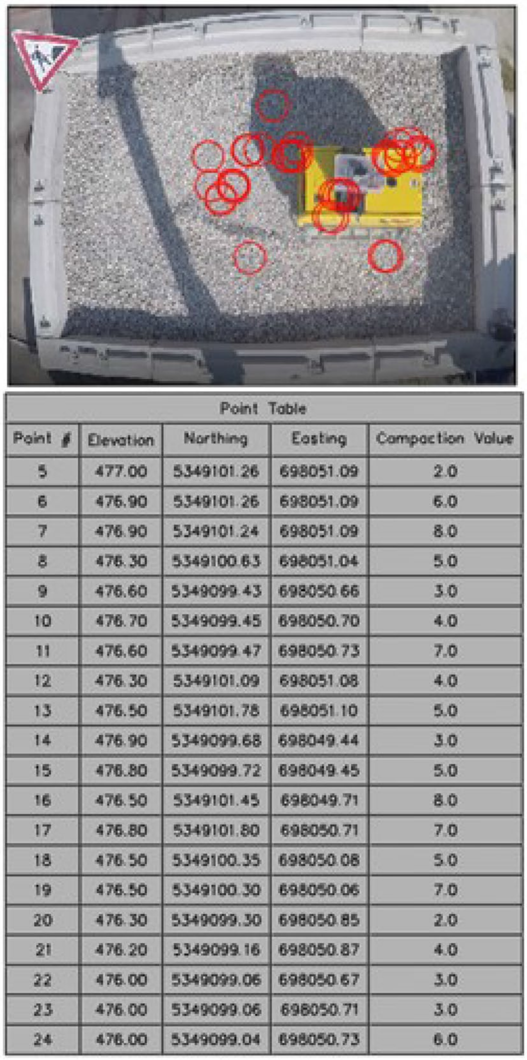
EIGENSCHAFTSSÄTZE

Compaction Value

Compaction Value 6

Fig. 14 Digital terrain model with compaction factor as input with the test area (blue circle—see Fig. 13). This was done using the Autodesk Infrastructure and Civil 3D applications, which were used to generate the DTM from a point cloud. Subsequently, a coordinate-based surface was defined in Civil 3D, to which a compaction value was assigned. The resulting surface is shown in Fig. 14, where a bird’s eye view of the construction site gives an overview of the entire test area.

2. The data generated in this way were exported from Civil 3D using the *.ifc data format. The file obtained in this way was limited to the relevant information and converted into a data format that is readable by the vibratory plate and the machine control of the excavator. For this purpose, a python script was used. The resulting *.csv-file was then transferred to the vibratory plate.
3. The vibratory plate and the excavator are able to process and use the information and to move independently. By measuring the superstructure acceleration of the vibrating plate, conclusions about the current compaction state can be drawn.
4. Based on these measurements, the vibratory plate executed the given work task. During execution, the compaction value was obtained locally by the vibratory plate. Matched with the GNSS position, the compaction value is stored locally in a documentation *.csv-file, which has the structure of a point cloud.
5. This file was then transmitted by the vibratory plate and imported directly back into Civil 3D. The result of the import, individual compaction points, and the associated compaction values is shown in Fig. 15. The scattering of the compaction values is due to the incompatible soil used in the test bed.



Point Table

Point #	Elevation	Northing	Easting	Compaction Value
5	477.00	5349101.26	698051.09	2.0
6	476.90	5349101.26	698051.09	6.0
7	476.90	5349101.24	698051.09	8.0
8	476.30	5349100.63	698051.04	5.0
9	476.60	5349099.43	698050.66	3.0
10	476.70	5349099.45	698050.70	4.0
11	476.60	5349099.47	698050.73	7.0
12	476.30	5349101.09	698051.08	4.0
13	476.50	5349101.78	698051.10	5.0
14	476.90	5349099.68	698049.44	3.0
15	476.80	5349099.72	698049.45	5.0
16	476.50	5349101.45	698049.71	8.0
17	476.80	5349101.80	698050.71	7.0
18	476.50	5349100.35	698050.08	5.0
19	476.50	5349100.30	698050.06	7.0
20	476.30	5349099.30	698050.85	2.0
21	476.20	5349099.16	698050.87	4.0
22	476.00	5349099.06	698050.67	3.0
23	476.00	5349099.06	698050.71	3.0
24	476.00	5349099.04	698050.73	6.0

Fig. 15 Data points with position and compaction factor as output

5.3 Step-wise development

Starting with a vibratory plate controlled through a shaft, the automated system was developed in a step-wise approach, as seen in Fig. 16. It illustrates the movement of the automation

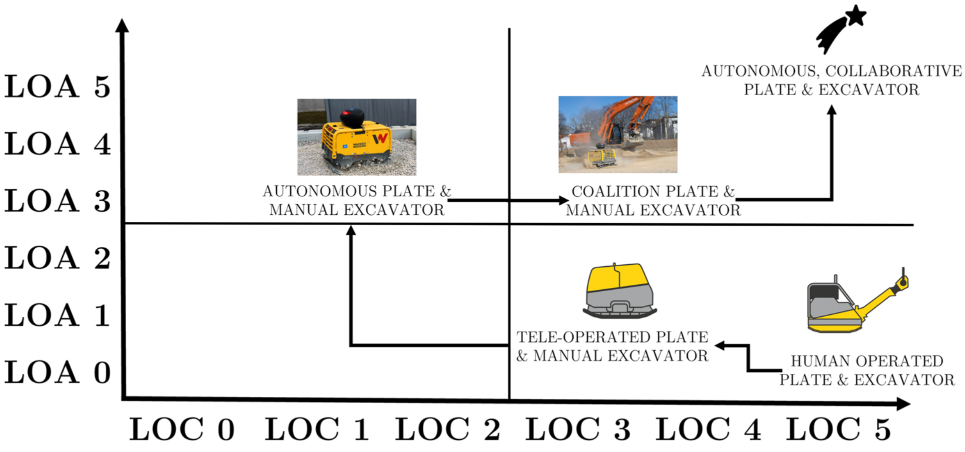


Fig. 16 Development steps from a manual to fully automated and collaborative vibratory plate

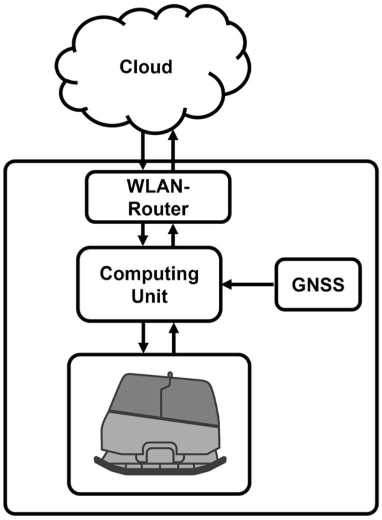


Fig. 17 Hardware structure of the vibratory plate

process within the automation–collaboration matrix and how the proposed development approach was implemented to establish a more efficient process.

As described above, as a first step, the plate is modified to be controlled remotely by replacing the shaft with an infrared remote control. Second, the vibratory plate is transformed into a cyber-physical system that can process, acquire, and document data using the hardware components shown in Fig. 17, and the Robot Operating System (ROS) version 2 (Robotics 2022). This constitutes the developmental step toward an autonomous plate, located in the upper left side quadrant of the collaboration–automation matrix. Here, a Computing Unit extend the vibratory plate via a machine interface, to be able to process the required information. In addition, a GNSS module generates data for global localization. Since the accuracy of the GNSS position depends on external influences, position determination can be improved with DGNSS (decimeter accuracy) or Real Time Kinematics (RTK) (centimeter accuracy) (Institute of Flight System Dynamics 2022). This involves using a base station to provide correction data that attenuates the environmental influences on the GNSS position. The correction data can be obtained from a service provider as well, but this does not offer the same level of accuracy as a base station. In this study, RTK delivers positioning data with a mean accuracy of 1.5 to 3.0 cm. Via a WLAN interface and a router, the vibratory plate communicates with an external computing unit.

With these adaptions, it is possible to specify a certain area to be compacted by the vibratory plate up to a certain compaction value with the help of an information model. This model combines the terrain information of a DTM with the property parameters of the work task in a BIM model. This information is used to carry out the compaction with the vibratory plate and transmit information about the degree of compaction back to the BIM model as well as model the earth surface with the excavator before compaction.

In its current final form, the plate and excavator can be described as autonomous coalition, located within the quadrant of the automated collaboration stars. The next step of the process would be to move toward an automated and collaborative plate and excavator process, where the excavator creates a leveled surface specified in the DTM (as-planed data). Meanwhile, the excavator provides an as-built data live stream to the vibratory plate, allowing for the first increment to be compacted. As both machines are very close in the shared workspace, a live stream of positioning data is exchanged and run through a geofencing algorithm, preventing collisions and constituting flexible dominant, shared decision-making. After completing compaction, the vibratory plate saves a complete as-built DTM file with surface

Fig. 18 Testing of the collaborative compaction process on a German construction site

and compaction values. Increments of the collaborative compaction process were already tested at a German construction site, as shown in Fig. 18.

6 Conclusion and outlook

The paper at hand investigates the interrelation of automation and collaboration in digital construction processes. Labor shortage, demographic change, and a deficit in productivity motivate automation in construction. While the automation of single tasks is on its way, there is a lack of collaboration between automated equipment and robots along the digital construction process. To foster the development of collaborating robots, definitions and classification criteria for automation and collaboration activities are given. With these criteria at hand, it was possible to classify scientific examples from the literature. On top of that, the paper introduces a prototyping framework for automated and collaborative equipment. The framework is thoroughly tested in an earthworks case study consisting of automated and collaborative excavation and compacting of an area.

Through the collaboration of an automated excavator and vibratory plate, it was possible to simultaneously execute the ‘excavation’ and ‘compaction’ task, speeding up the overall earthworks process by a factor of almost two. Alongside improved productivity, the high degree of automation allowed for increased construction site safety, as fewer workers are exposed to dangerous workspaces. Finally, the quality of the process is increased as well, including continuous quality checking and integrated documentation of as-built data in BIM models.

Further applications of the framework lie in construction scenarios where multiple machines or robots work in close proximity, well-defined sequences or even work sharing. Therefore, road or railway construction with its linear site design and clear set of constraints is predestined for Cobots. It is imaginable, that in the future trucks, feeder, finisher and compactors form a fully automated, collaborative work system with minimal human intervention.

Future research endeavors can focus on three successive areas. First, the classification criteria can be applied to further use cases to increase the rigor within the discussion of automation and collaboration. Widespread construction literature, like Bock and Linner (2016), offer multiple robotic applications, which can be analyzed regarding collaboration potential. A transfer to other industries could additionally increase the robustness of the proposed criteria and foster a better overall understanding. Especially use cases involving more than two entities could further increase the applicability of the framework. Possible outcomes could be LOC and LOA ranges (minimum and maximum values) for operating scenarios with multiple machines. Second, the industrial development of collaborative and highly automated equipment needs a more extensive framework than the generic prototyping framework presented in this paper. Although the prototyping framework fulfills all requirements in a scientific setting, the level of detail should be increased for industrial users. Third and last, the power of multi-modal, shared models, like BIM models, is still largely underrated. A shared and common knowledge base offers a lot of opportunities for collaboration and automation. Spreading and facilitating the use of these models in practice forms a reliable basis for further automation and collaboration scenarios in organizational and technological contexts.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data availability All necessary data is included in this paper, continuative data is available at reasonable request from the authors.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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