Enhancing Decision-Making for Human-Centered Construction Robotics: A Methodological Framework

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Abstract –

While the Architecture, Engineering, and Construction (AEC) industry is increasingly aware of the rising demands for productivity and human-centered construction improvements, the holistic adoption of robotics as a fundamental strategy to address these challenges has not yet reached comprehensive fruition. This paper therefore introduces a methodological framework aiming to address the industry's pressing need for a systematic approach for assessing the feasibility of integrating robotics into human-centered construction processes. It aims to enhance decision-making regarding the degree of automation in human-centered construction processes, ranging from partial to full robotization or non-robotization. The framework is characterized by a more holistic end-to-end data-/workflow and therefore adopts a multifaceted approach, leveraging BIM-based planning methodologies and integrating new technologies [e.g., Motion Capturing (MoCap), work process simulation software incorporating Digital Human Models (DHM), self-developed conversion/interfacing software and more] that have not been widely used in the industry to date. Subsequently, the framework is evaluated in a real-life bricklaying construction process to ensure a more application-based approach. Overall, the framework advances current construction processes with a more inclusive and conscious technology infill to empower construction professionals with the workflow and corresponding tools necessary for the practical integration of robotics into human-centered construction processes.

Keywords –

Decision-Making; Framework; Workflow; AEC Industry; Robotics; Building Information Modeling (BIM); Human-Centered; Motion Capturing

1 Introduction

The AEC industry is a major contributor to the global economy facing a variety of challenges. Socially, it involves a lack of skilled labor and challenging work conditions [1]. Economically, it lags in productivity, digitization, and faces obstacles in high inflation environments [2]. Moreover, the housing demand outpaces supply, causing significant increases in rental prices [3]. Ecologically, the industry is one of the most resource-intensive industries and therefore significantly affecting climate targets [4].

Considering these challenges, while recognizing the need for transformative measures (especially regarding Industry 4.0 to 5.0/6.0 shift), the industry is advised to explore new technologies and create more human-centered construction processes to counteract aforementioned challenges [5, 6]. Therefore, robotics as one of the most disruptive technologies across a multitude of industries offers the potential to address several challenges accordingly.

However, to introduce robotics in construction and at the same time ideally foster more human-centered construction processes (incl. better, ergonomically favorable work conditions), it is crucial to address the inherent industry limiting factors (e.g., weak business/use cases, low research budgets, high-risk with partly immature technology, data inconsistency and lacking interfacing capabilities, dynamically changing on-site conditions, lack of upstream feasibility assessment etc.) that impede an appropriate transition and subsequent integration [5]. In this regard, research has already been undertaken to address the aforementioned problems. However, most research lacks in terms of formulating a systematic and holistic approach for integrating robotics into human-centered construction processes. This deficiency is compounded by inadequate technology utilization, insufficient attention to human factors, coupled with a lack of cross-domain knowledge utilization, which further exacerbates the problems and ultimately leading to insufficient workflows.

Therefore, a critical research question emerges: How can the industry assess the feasibility and subsequently enhance decision-making regarding the integration of human-centered construction robotics?

This paper aims to give a preliminary answer to this question with a structured approach (methodological framework) characterized by a more holistic end-to-end data-/workflow. This enables enhanced decision-making, strategically incorporating technologies to assure an appropriate and more future-proof adoption as well as feasibility assessment of robotics in construction. By doing so, the industry can achieve a higher efficiency, while acting human-centered, ensuring its continued resilience in the face of evolving economic, social, and environmental landscapes.

2 Related Work

The AEC industry and affiliated research features a variety of methodologies aiming to counteract aforementioned industry challenges and associated limiting factors (see section 1). One example is the Building Information Modeling (BIM) methodology utilizing 3D-models (incl. geometric and correlating semantic data/information) to streamline multidisciplinary work processes throughout the entire building life cycle. Building up on the BIM-methodology, there are further ones based on it and aiming to enhance decision-making towards a higher adoption of robotics in construction through various improvements (e.g., enhanced data/information flow incl. added process data/information leveraging BIM-based planning methodologies etc.) [7, 8, 9, 10].

Despite those methodologies, it is recognizable that the adoption of (industrial) robotics in construction is still significantly lower compared to other industries (see Figure 1, “Others”) [11].

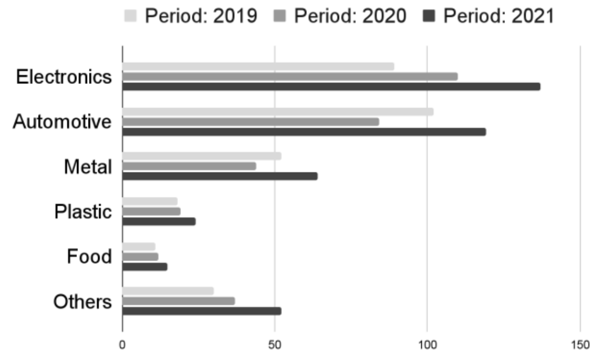

Figure 1. Annual installations of industrial robots by customer industry worldwide (1,000 units)

In this context, one derivation the related work emphasized is the potential of adequate data preparation, accumulation, and interfacing capabilities already in early planning phases to enable enhanced decision-making and more holistic end-to-end data-/workflows.

In addition, Industry 5.0 proclamations call for a necessity towards more human-centered construction processes where ergonomic assessments come into play and are mutually respected in the digital as well as physically applied context to improve ergonomically unfavorable work conditions. This aspect is currently hardly considered in traditional construction processes (especially regarding the associated data-/workflow).

Subsequently, a structured data-driven approach (methodological framework) needs to be established, that incorporates work and machine process requirements in early planning phases, aiming to holistically address aforementioned industry challenges and associated issues (respecting Industry 5.0 proclamations) through consecutive economic and ergonomic assessments of construction processes.

3 Methodology

This paper builds upon a comprehensive research methodology (RM, see Figure 2) considering diverse

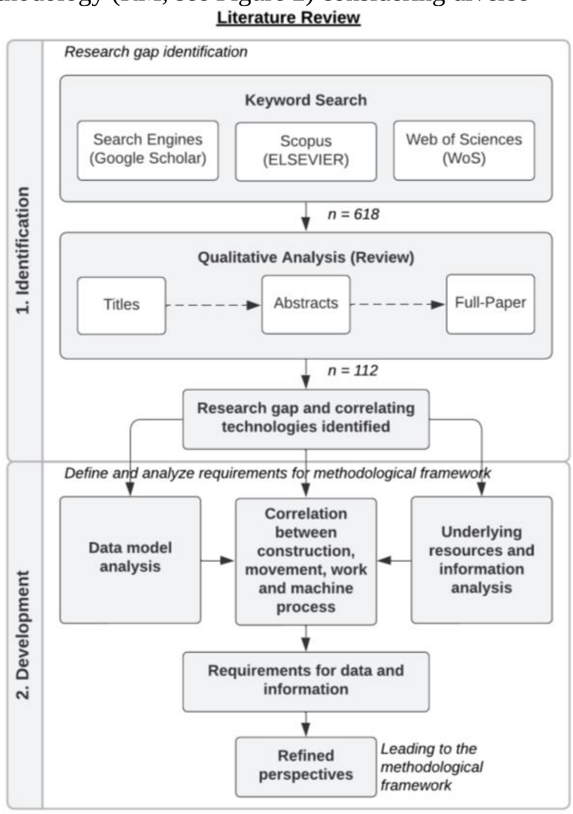

Figure 2. Research methodology (RM)

sources and analytical approaches to identify technologies which ideally could enable enhanced decision-making for integrating robotics in human-centered construction processes.

Therefore, the RM starts with a literature review through search engines focusing on peer-reviewed high impact articles (2018 - mid 2023) ensuring a meaningful, thorough, and differentiated exploration. The selected period is chosen to encompass the latest literature considering more application-oriented and ideally already (empirically) validated literature.

The initial search used specific keywords ("advanced search", incl. boolean operators, see Table 1) aiming to find relevant titles (after deleting duplicates = n = 618) before the abstract and subsequently full paper for a more in-depth selection was reviewed in an incremental approach (qualitative analysis).

Table 1. Keywords used for the keyword search ("Advanced Search", Accessed: December 2023)

Framework AND	**Production** AND	**Construction**
"framework"	"production"	"construction"
OR	OR	OR
"methodology"	"robotic"	"architecture"
OR	OR	OR
"decision"	"automation"	"building"

The identified literature derived from the qualitative analysis (n = 112), revealed that certain technologies (total = n = 16, e.g., BIM-software, MoCap, work process simulation software incorporating DHM, conversion/interfacing software, Artificial Intelligence algorithms, agnostic robotic frameworks etc.) offer the potential for enhanced decision-making regarding the integration of robotics into human-centered construction processes. However, a lot of identified technologies are currently largely unutilized in the AEC industry (e.g., MoCap).

The subsequent development of the methodological framework incorporated a final analysis of the identified technologies regarding their data models (e.g., tabular, hierarchical, entity-relationship etc.), alongside with underlying resources and information (e.g., Level Of Information Need, LOIN etc.) to consecutively weave them into a data-driven methodological framework respecting the correlations and interplay between construction, movement, work and machine processes which was particularly highlighted in literature as an essential approach. Concluding the overall literature review, the RM ended with the synthesis of necessary requirements for data and information needed to develop the methodological framework accordingly and derive associated relationships from it.

4 Methodological Framework

Through the literature review (see section 3, incl. associated qualitative analysis) and assimilation of insights gained, a multitude of technologies were identified as pivotal contributors or enablers for enhanced decision-making for integrating robotics into human-centered construction processes. Subsequently, the overarching perspectives (n = 5) were derived from the analyzed technology potentials for robotic integration (weightings) and their number of mentions (see literature review and RM). Accordingly, these perspectives as well as corresponding technologies are used in the methodological framework and listed below:

- **Construction perspective:** Utilizing industry-standard BIM-based planning methodologies and associated software (e.g., Autodesk Revit, Graphisoft Archicad, BlenderBIM etc.) with correlating data models (Industry Foundation Classes, IFC, standard developed by buildingSMART for vendor-neutral data sharing) can enable the adoption of more holistic planning respecting the entire life cycle of a building and subsequently enhancing planning, coordination, and execution of robotic tasks by offering a detailed building representation (incl. geometric and semantic data/information).
- **Movement perspective:** Utilizing MoCap systems (e.g., Xsens, Vicon, OptiTrack, Theia Markerless etc.) can enable the integration of explicit construction process data (Biovision Hierarchy, BVH) derived from real-world applications and hereby enhance human-centered (especially ergonomic) planning potentially enhancing construction processes with human-robot-collaboration (HRC) based processes.
- **Work process perspective:** Utilizing work process simulation software incorporating DHM (e.g., ema Work Designer etc.) can enable the integration of economic and ergonomic assessments within a simulated work process environment (incl. robotic and HRC processes) to enhance human-centered planning ideally enhancing construction processes with economically and ergonomically assessed processes.
- **Machine perspective:** Utilizing (vendor-neutral or agnostic) robot frameworks for programming, simulating, controlling, and monitoring production processes (e.g., ROS, RoboDK, HAL Robotics Framework etc.) can provide an intuitive and user-friendly way for the subsequent utilization of robotics in an end-to-end data-/workflow.
- **Interface perspective:** Utilizing conversion or interfacing software (e.g., based on Application Programming Interface programming etc.) can enable the integration of multidisciplinary data

sets within a construction process.

Despite the added value these technologies offer, they are currently still largely applied independently from each other and not interlinked in any tangible, overarching methodology within the AEC industry. Therefore, data and correlating information is often siloed, not appropriately prepared (e.g., fragmented due to different naming conventions etc.), accumulated and interfaced regarding downstream processes. Subsequently this methodological framework aims to integrate and interface aforementioned technologies and associated perspectives with traditional construction processes incorporating adequate data preparation and accumulation possibilities through enriched data sets (semantic enrichment) adding additional contextual information.

Considering the identified technologies, derived perspectives and traditional construction processes, the methodological framework starts with defining the project requirements (see Figure 3). In the construction context, this involves conveying the client's design intent via documentation to the planner (construction perspective). This sets the stage for the subsequent CAD-/BIM-based modelling of the desired building, building component or product design. During this stage, the work and machine process perspective become crucial in establishing the requirements for incorporating related process data/information in early planning phases to mitigate potential correction loops. Here, the utilization of semantic enrichment via custom property sets (related to domain-specific entities) leveraging BIM-based planning methodologies becomes essential, offering the capability to automate the retrieval and inference of missing or needed data/information (LOIN) for downstream processes. Custom property sets are generally defined using several inputs (e.g., name, instances, entities/classes and the underlying properties which can be freely chosen and described using strings, floats, Booleans, integers etc. depending on the desired property). The custom property sets are part of the IFC data model (based on the EXPRESS data modeling language and overarching STEP data model; incl. attributes, relationships, property sets etc.) which can inherent geometric and semantic data/information describing the meaning of its instances. Therefore, the IFC data model can serve as a repository for the infused work and machine process requirements. The work and machine process requirements can involve data/information concerning building components (e.g., dimensions/scales, weights, assembly orders etc.) which are necessary to align consecutive process requirements with the intended design established in the CAD/BIM-based planning phase (construction perspective). For instance, can infused machine requirements regarding the maximum layer height in a concrete 3d-printing use-case or a maximum gripper width (robotic end effector) in a brick-laying use-case inform the planner about the feasibility of a robotic execution and possibly enhanced economic and ergonomic construction process. In addition, these requirements are not only embedded into the IFC data model via custom property sets but also in an Information Delivery Specification (IDS) to define exchange requirements within an openBIM process enabling a consecutive IDS-rule/specification-based model checking regarding related work and machine process requirements (so-called "specifications"). The IDS allows the definition of certain specifications described by "facets" (related 6 types: entity/class, attribute, classification, property, material, and relation/part of). To define a specification or facet type (in this case property) there is a so-called description (human readable information to elaborate on the requirement), applicability (type of object the specification applies to) and requirement (which information is required) inputs needed. These specifications can refer to the work and machine process requirements subsequently be used with a model checker (e.g., established with IfcOpenShell as open-source software library for processing the IFC data model) to check if the requirements in the IFC are matching the ones defined in the IDS. This step can improve communication, avoid errors, and facilitate better collaborations throughout the entire construction process by establishing data/information consistency and retrieval when needed.

However, this model checking routine should not limit the planner in terms of their design freedom. Therefore, a data exchange to the next planning phase (work process perspective) is still possible even when the requirements are not matched due to the approach that this framework should establish an enhanced decision-making but not limit the design. Subsequently the planner could intentionally design a building which does not match with any of the work or machine process requirements but consciously deciding to continue with it due to their individual design intention.

Afterwards the IFC (incl. the enriched semantics) is imported into a work process simulation software incorporating DHM (CAPP, work process perspective) and enabling work process planning, simulation, analysis, and optimization regarding human-centered construction processes (e.g., bricklaying, concreting, painting, plastering etc.). However, due to interoperability issues regarding the IFC (enriched semantics), the file is converted through a conversion/interfacing software into a software-readable XML-format (structured data). The conversion/interfacing software makes it possible to check for specific relations and properties among the IFC entities. In addition to the advantages a CAPP software incorporating DHM can offer (e.g., enhancing task allocations, capability of assessing economic and ergonomic aspects etc.) there is also the possibility to import and work with MoCap recordings, enabling an explicit representation of real-life construction processes to plan more application-based, human-centered, and inclusively.

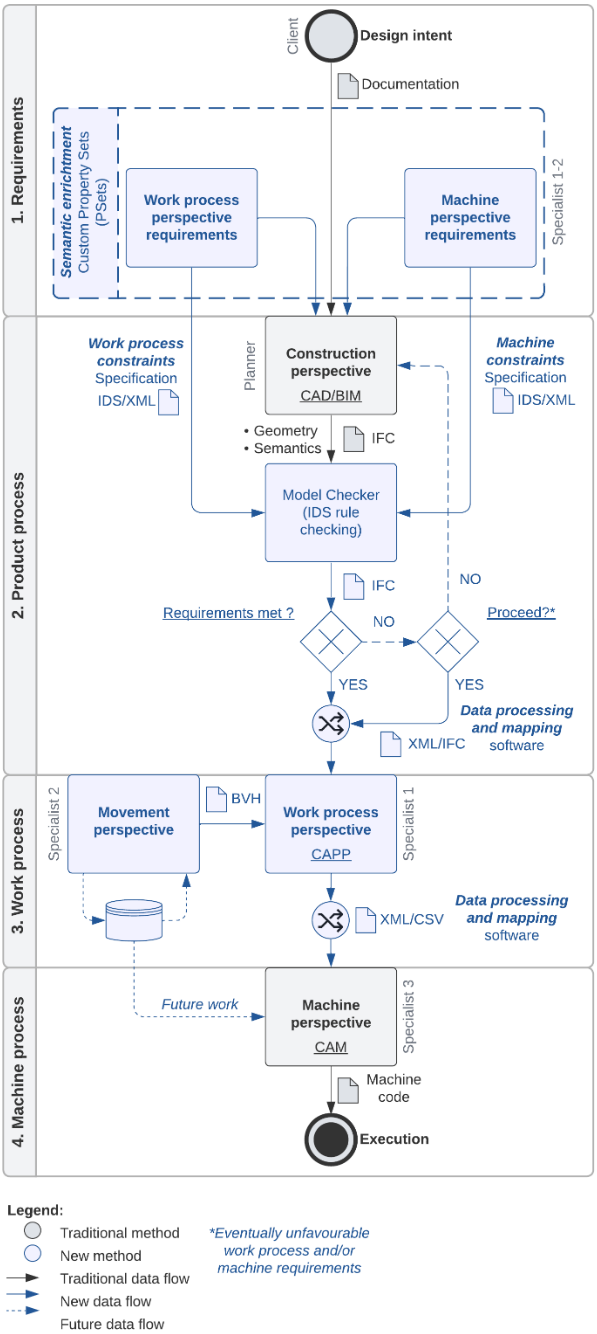

Figure 3. Methodological framework

Therefore, the proposed methodological framework emphasizes on using this capability of integrating MoCap data (BVH) strategically to mitigate diverse economic and ergonomic risks (e.g., derived from repetitive, mundane, and physically intense tasks etc.). In this context the methodological framework implemented a database (movement perspective) utilizing Python and SQLite, as well as a necessary database management system (DBMS) to subsequently be used to store, but also push and pull data/information as needed. This database can be used as a MoCap recording repository for generic as well as replicable human-centered construction processes and therefore future application. Utilizing MoCap data/information of a human-centered construction process as well as the IFC (incl. enriched semantics), the CAPP software can make a work process assessment considering economic (e.g., timely aspects via MTM-UAS) and ergonomic (e.g., ergonomic aspects via EAWS) guidelines to support with the decision-making regarding the integration of robotics into human-centered construction processes. Furthermore, a robotic construction process can be modelled and compared in the CAPP software leading to a robot simulation which can be exported as a CSV (non-proprietary open format) and subsequently converted/interfaced with the data compartments of the robotic framework. This step includes the conversion of all prepared and accumulated data/information (coordinates/orientation frames for automated toolpath/trajectory planning; action states; task allocations; component information such as sizes, weight etc.) derived from previous processes and the robot simulation in the CAPP software to interface it accordingly for simulation (e.g., checking on singularities or orientation frames being out of reach etc.), programming, control and monitoring. Subsequently the agnostic robotic framework (CAM, machine perspective) enables the program execution and production as desired while building up on prepared, accumulated, and interfaced data/information and thereby accelerating the robot programming.

5 Evaluation and Results

The methodological framework is evaluated with a bricklaying construction process since the use-case is globally applied and holds a pivotal position within the AEC industry owing to its historical importance and extensive utilization. Furthermore, bricklaying as a construction process is one of the most repetitive as well as physically demanding tasks, therefore tends to be economically and ergonomically unfavorable which leads to a need for optimization.

In this context the evaluation of the methodological framework focusses on a load-bearing brick wall assembly (brick size: 24 x 11,5 x 11,3 cm) which is derived from the planner's building model (CAD/BIM, IFC, Autodesk Revit) and a result of the previously conveyed design intent via documentation from the client. In the next step the model (load-bearing brick wall) is semantically enriched through custom property sets. The infused properties refer to work and machine process requirements [e.g., "assembly order" for task allocations; "brick weight" for ergonomic assessment and consideration of robotic payloads as well as moment of inertia and therefore appropriate toolpath/trajectory planning; "brick dimensions" (length x width x height) for ergonomic assessment and robotic end effector conformity checks e.g. based on the gripper width etc.] to mitigate potential correction loops and enable a consecutive feasibility assessment regarding a robotic construction process. The aforementioned properties are also implemented as part of an IDS (specification) which consecutively is used with an implemented model checker (utilizing IfcOpenShell) to check the IFC if the custom property sets are created accordingly or not.

Afterwards the planner can decide (based on the issue tracking) if he/she wants to continue with the IFC or in case the properties are not set up yet, to return to the CAD/BIM software and adjusting it accordingly.

Afterwards the implemented conversion/interfacing software enables an appropriate data processing and mapping (based on the IFC data model) towards the work process planning (CAPP).

In the next step the model (IFC) is imported into the work process simulation software which incorporates DHM (CAPP, ema Work Designer) and can be used as basis for economic and ergonomic assessments. In this use-case the simulation environment and procedural accuracy is enhanced through explicit movement data/information stored in the BVH-database serving as a human-centered construction process repository. For this purpose, the bricklaying construction process is recorded using an inertial measurement unit (IMU) based MoCap system (Xsens Awinda by Movella). The MoCap recordings are done with a construction/masonry worker (male, 186cm body height) with 13 years of experience within a laboratory setting to establish as viable results as possible.

In this context two process variants were recorded: the first one (see Figure 4 and 5)utilizes a pallet with varying brick positions (4 corners of the pallet with 8 bricks on each corner), whereas the second variant refers to various pick and place heights to draw assumptions based on different heights in relation to the construction worker's body height (see first process variant in Figure 4 and 5).

The process variants are therefore abstracted based on standardized bricklaying construction process practices (incl. a pallet as pick-up setup, plank referring to the insulation offset layer needed and maximum bricklaying height of 170cm referring to the eye-level of the construction worker). After the MoCap recordings are stored in the BVH-database and imported into the CAPP software, the evaluation of the bricklaying construction process based on the model (IFC) can be initiated.

Figure 4. First process variant, human-based, manual (left: setup, right: MoCap recordings)

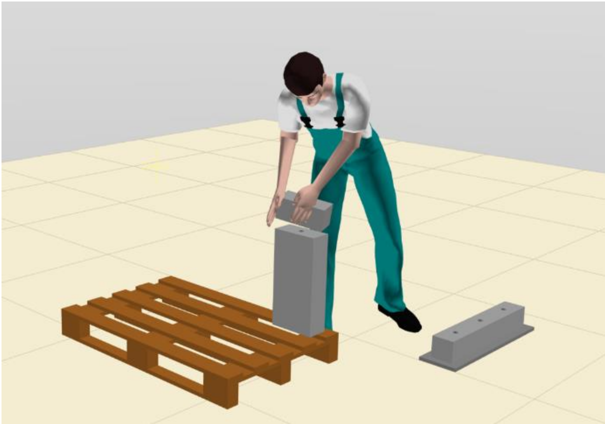

Figure 5. First process variant (CAPP software incorporating DHM, ema Work Designer)

Subsequently, the virtual ergonomics of aforementioned process variants can be evaluated by utilizing the Ergonomic Assessment Work Sheet (EAWS). As the EAWS score recommends a redesign of working processes or environments within a score of 25-50, processes with assigned scores more than 50 shall be urgently modified. Regarding the EAWS analysis of the first process variant, the following table (see table 2) summarizes the influence of the brick positions on human ergonomics as well as required process times (according to the 4 corner positions of the bricks).

Table 2. EAWS Score based on MoCap recordings from the four subprocesses in the first process variant

Brick position/ subprocess	EAWS Score for 8-hour shift
front left	128,5
front right	154
back left	123
back right	116

The comparison of the four subprocesses correlating to the four different brick positions on the pallet, results in a respective EAWS score of more than 100, which indicates an urgent need for a work process redesign.

The second process variant investigates the influence of the bricklaying height in relation to the construction worker's body height. The worker picks 15 bricks one by one from the front left brick position of the pallet, whereby the maximum stacking height on the pallet comes to 8 bricks. The resulting EAWS score for each subprocess is presented in Table 3.

Table 3. EAWS Score – MoCap results from the subprocesses of the second process variant

Brick ID/ subprocess	EAWS Score for 8-hour shift
1	90
2	71,5
3	99
4	59
5	74
6	66,5
7	81,5
8	66,5
9	36,5
10	35
11	47
12	47
13	79,5
14	58
15	77

Table 3 reveals an EAWS score under 50 in brick 9, 10, 11 and 12, which relates to subprocesses with predominantly straight postures of the human worker without bending or working near the ground.

Furthermore, the table 4 shows the required execution time of the human-based manual process (referring to the first process variant) and the same process but executed by a collaborative robot (Yaskawa HC10, incl. a process variant with adapting the robot velocity with a maximum of 1m/s).

Table 4. Required execution times of various processes

Executor	Time [s]
Human	69
Robot	44
Robot (velocity adoption)	60

These ergonomic and economic assessments based on virtual ergonomics via EAWS score and execution times are derived from CAPP software (ema Work Designer) and subsequently enable an enhanced decision-making concerning the applicability of robotics in human-centered construction processes. In this use-case, the EAWS score indicates (see table 2 and 3) a need for a work process redesign and therefore a new task allocation which is ergonomically more favorable. Therefore, the process was opted with a second one (see Figure 6) where only the collaborative robot (Yaskawa HC10) was executing the construction process accordingly. This led to an optimization in execution time (see table 4) and no unfavorable ergonomic processes since only the robot is executing the process without human intervention.

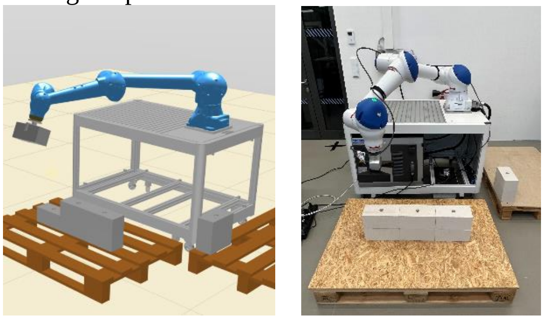

Figure 6. Second process variant, robot based (left: CAPP software incorporating DHM, ema Work Designer, right: real-world execution)

However, the EAWS score also indicates that certain subprocesses (see table 3, grey markings) are not as unfavorable as others, which means that the human could still overtake certain subprocesses in a HRC process variant. However, in the second process executed by the robot, but also in the suggested process variant (HRC), the human could be freed from ergonomically unfavorable as well as repetitive processes and overtake more value adding processes. Moreover, the human could still be part of the process for monitoring purposes making sure that the brick wall is straight (e.g., utilizing a water scale etc.). Furthermore, nowadays the human still offers the highest degree of flexibility since no reprogramming for tasks is needed and the human can react immediately to unforeseen circumstances and is therefore in many use-cases irreplaceable.

However, at the end the decision-maker must decide for a task allocation supported by the economic (execution time) and ergonomic (EAWS) assessments based and optimized through the methodological framework.

Finally, the machine process was evaluated and established using an agnostic robotic framework (HAL Robotics Framework, Grasshopper Plugin). In this step the simulated robot tasks from the previous CAPP software (ema Work Designer) were processed and mapped using the implemented conversion/interfacing software. Here, the robot simulation results including necessary orientation frames etc. could be exported and mapped to a CSV to consecutively weave them into a visual algorithm editor (Grasshopper) where the corresponding coordinates could be automatically interpolated to generate a curve used for the robot toolpath eventually resulting in a more efficient execution.

6 Discussion and Outlook

The IMU-based MoCap system of the methodological framework is commonly used for applications with a required setup simplicity. However, this simplicity comes with a loss in accuracy. Due to external and internal influences, calculation-driven stochastic errors accumulate over time and lead to a drift and therefore inaccuracy in position determination. That is why in industrial MoCap applications, mostly camera-based (optical) systems are used due to lower error rates (incl. lower time-depending drifts). Considering the accuracy and reliability, a camera-based (optical) MoCap system should be considered in the future.

Moreover, the methodological framework currently works with an implemented IDS-rule/specification-based model checker which works for all IFC entities. Therefore, a direct checking routine regarding a certain geometric representation (e.g., IfcSweptSolid, IfcFacetedBRep etc.) would be possible (currently only checking for custom property sets). However, due to a multitude of geometric representations within an IFC, this possible improvement has to be thoroughly evaluated before implementation.

Finally, the methodological framework could be further enhanced with a software extracting specific orientation frames from the MoCap recording (incl. AI algorithms for semantic action segmentation and classification of demonstrations) which correspond to a desired position and can be utilized as toolpath/trajectory planning basis. This could serve as an alternative kinesthetic and user-friendly programming method enabling users to reprogram without specialized expertise. In this context one could benefit directly from the construction worker's experience which forms the basis for the robot program and consecutive execution.

7 Conclusion

The methodological framework offers a systematic and holistic approach to enable enhanced decision-making regarding the integration of robotics into human-centered construction processes, strategically incorporating technologies while assuring an appropriate data/information preparation, accumulation, and interfacing capabilities. By doing so, it aims to promote a higher adoption of robotics in construction. Compared to existing studies, this approach presents significant contributions by providing a more holistic end-to-end data-/workflow that not only addresses decision-making but also emphasizes the strategic incorporation of cross-domain knowledge (e.g., utilization of software mainly used in the automotive industry, ema Work Designer etc.), human factors and data management. Moving forward, further refinement and implementation of the critical aspects (see section 6) will be essential for maximizing the effectiveness and applicability of the proposed framework.

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