Towards interfacing human centered design processes with the AEC industry by leveraging BIM-based planning methodologies

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Abstract –

Digital workflows in the Architecture, Engineering and Construction (AEC) industry have been working with a wide range of software solutions trying to enable a Design-to-Production (DtP) end-to-end data flow. Thereby, state-of-the-art software solutions attempt to streamline the design and production processes accordingly.

However, most digital workflows lack in terms of adequate sequential data preparation, agglomeration, and interfacing capabilities for consecutive design phases. These issues result in long, tedious correction loops, a wide range of software solutions and extensions to mitigate the issues. In addition, many digital workflows do not consider or integrate construction, production and machine relevant data holistically (respectively geometry and semantics). In this context, the production relevant data in from of human-centered work process data referring to digital human models (DHM), derived human abilities, safety and ergonomic criteria are often neglected. However, this is essential to interface the construction, human and machine relevant data in a holistic manner.

This paper therefore proposes a DtP-workflow which is intended to solve some of the issues by interfacing relevant software solutions incorporating construction, production (including DHM and more) and machine relevant data in a holistic manner using a Building Information Modeling (BIM)-approach (based on the IFC schema). In this regard, the DtP-workflow aims to reverse common top-down digital workflows by considering and integrating the relevant data for consecutive design phases from the beginning. Subsequently, the DtP-workflow should achieve a reduction in planning effort.

Keywords –

Architecture Engineering and Construction (AEC) industry, Building Information Modeling (BIM), Digital Human Model (DHM), Interoperability

1 Introduction

The AEC industry plays an integral part in the worldwide economy by being not only a major employer, but also responsible for critical infrastructure and is thus systemically relevant. That is why the industry is under enormous economic and social pressure. Socially, it suffers from an omnipresent shortage of skilled labor due to the demographic change and is particularly aggravated by physically intense and dangerous work conditions [1]. Economically, the overall increased productivity rates are lower than in other industries and simultaneously experiences one of the lowest degrees of digitalization [2]. In addition, the growing demand for housing has not been satisfied yet, which has led to increasing real-estate prices [3].

To counteract the aforementioned inhibiting factors, the performance of AEC related tasks has to get more efficient, persistent, quality consistent and human-centered to secure a higher value creation, thereby significant productivity gains and acceptance.

In this context, productivity losses are often caused by interoperability issues between different software solutions. Data is siloed in different software solutions and databases causing data redundancies, as well as inconsistencies. Moreover, different file formats, data structures and naming conventions lead to data fragmentation.

Current research on improving interoperability and thereby including common data standards (e.g. BIM) are already conducted. However, there is still a need to fully enable a seamless data flow from design to production considering and integrating (not only) construction, but also production and machine relevant data.

The research gap therefore consists of a lack of process relevant data preparation, agglomeration, integration, exchange capabilities and adoption of new technologies (e.g. BIM) to enable an effective, collaborative and seamless workflow. Subsequently, enabling the aforementioned could save millions of working hours and eventually led to more projects being delivered on time and within budget [4] [5].

Therefore, this paper proposes a DtP-workflow, aiming towards a beneficial economic and social impact for the AEC industry by bridging interoperability gaps considering, as well as integrating construction, production, and machine relevant data in early design stages. In this context, it should illustrate a first attempt of interfacing work process simulation software (including DHM and more) with AEC industry related BIM-authoring software and eventually machine control capabilities.

2 State-of-the-art

2.1 Digital workflow tools

Nowadays, a digital workflow in the AEC industry consists of various sequential value adding steps (e.g. planning, detailed planning, production planning, construction or building operation etc.) and therefore incorporates a wide range of different software solutions. In this context, the ISO family of standards (IFC schema and process standards), common data environments and novel management approaches such as lean construction introduced strategies allowing a more integrated workflow. Moreover, digital, parametric planning and modeling using BIM approaches are the basis for integrated planning and communication throughout the value chain. Nevertheless, such approaches usually require complex adaptations cross compartments and value-added steps [6] leading to concepts such as Design for Manufacturing and Assembly (DfMA), Robot Oriented Design (ROD) and considering construction as an integrated production system [7].

In addition, there are further identified challenges regarding the overall data interoperability [8] such as loosely defined object definitions, the coverage of BIM authoring tools and varying levels of parameterization. Furthermore, the introduction of semantic web technologies into the AEC sector are likely to overcome these problems by introducing a metadata abstraction layer, able to describe heterogeneous data sources [9].

Moreover, possibilities of using simulation software solutions, ever better integration of BIM-to-machine/robot software pipelines and the use of robotic frameworks can further facilitate integration.

In the following sections AEC industry related state-of-the-art software solutions (alias: digital workflow tools) are described further and intended to be used in the proposed DtP-workflow (section 3 and 4). Moreover, correlating challenges are synthesized to identify digital workflow determining bottlenecks which the DtP-workflow is intended to tackle accordingly.

2.1.1 Building Information Modeling (BIM, construction perspective)

In general, an AEC project involves various stakeholders and is therefore increasingly reliant on a BIM-approach incorporating the IFC data model schema to eventually assure a better-information flow throughout the design phases. That is why many sectors started to require BIM in AEC projects and aiming to establish it as a standard practice for the industry since recent years [10].

BIM-based data interoperability is mainly facilitated by the common IFC data model schema which defines AEC industry-specific entities and relations (Industry Foundation Classes) [11]. It allows the creation of BIM models which serve as a repository for all data related to the building itself as well as the construction process. That is why this data model is considered the de-facto standard for exchanging data through an openBIM collaboration process [12].

The data model can utilize existing construction domain-specific entities which can be complemented by custom property sets in order to store all production-specific information (e.g. Materials, Names, Surfaces, Colors, Coating Areas, Gross Areas, Net Areas, Professions, Deliveries, Categories etc.).

Exchange requirements are implemented through a separate schema file (STEP or XML) which makes it possible to check for specific relations and properties among the IFC entities. This so-called 'level information need' as mentioned in [13] is - in terms of the IFC - implemented through either a Model View Definition (MVD), or an Information Delivery Specification (IDS).

In model-based workflows issue management can be accomplished by contextualizing the issue with an entity In BIM-based workflows this can be implemented through the so-called BIM Collaboration Format (BCF). In practice BCF can be implemented as a file or web-service.

In accordance with the proposed DtP-workflow (section 3) and use-case (section 4), the mechanisms implemented by the Industry Foundation Classes offer a purposeful software solution.

2.1.2 Human-robot-work-process simulation (production perspective)

An AEC project can be also complemented by human-robot-work-process simulations enabling a holistic prospective and thereby human-centered planning process for production.

Planning systems with DHM such as ema Work Designer (emaWD) or process simulate can thereby detect ergonomic risks and are used to analyze and optimize the work process regarding ergonomics and productivity [14].

EmaWD (section 4) includes an integrated task library and a motion generator that allows the DHM to autonomously fulfil user-defined work tasks. Hereby, DHM with different abilities related to age (e.g. anthropometry, mobility, etc.) as well as various robots can be used to ensure an aability- and age-appropriate design of work processes and factories at an early stage [15] [16].

This step is essential to simulate, analyze and optimize task planning or allocations for human- and robot- related work processes in a holistic production related manner (including risk assessment, collision detection etc.).

Subsequently, such software solutions can be beneficial for the DtP-workflow by considering production in a holistic manner considering product, human and machine or robot in accordance to the production periphery.

2.1.3 Machine simulation and control (machine perspective)

An AEC project usually ends with the machine control and thereby subsequent production/realization of the intended project or product.

In general, there are two ways of programming such machines – either offline (e.g. remote via PC and underlying software solutions) or online (at the machine itself e.g. via Teach Pendant).

To establish an end-to-end data flow, an offline programming approach is to be chosen to make sure a sequential software solution usage is established accordingly.

In this context, vendor-.agnostic software solutions (e.g. frameworks) for simulating and partly programming/controlling (offline programming, e.g. Gazebo, RoboDK, HAL Robotics Framework, Robot Operating System ROS etc.) play a decisive role for testing new control algorithms, evaluate efficiency, safety, and robustness, as well as optimize the operational behavior [17] [18].

Nevertheless, the general user effort and correlating usage complexity depends heavily on the machine itself and associated Degrees of Freedom (DoF). An NC control for a CNC milling machine with three DoF can already be initiated seamlessly due to a standardized machine programming language (G-code), whereas the machine control with a robot is more difficult due to more DoF and different manufacturer-specific programming languages. However, this difficulty can be partly conquered by agnostic software solutions (robot frameworks, e.g. ROS, HAL etc.) as mentioned before.

In this regard the proposed DtP-workflow (section 3 and 4) is intended to use aforementioned agnostic software solutions (machine control via offline programming with framework) to prototypically execute a machine control (robot) with the advances of being simulation based and agnostic.

2.2 Resulting challenges of the digital workflow in AEC industry and underlying tools

The preceded research showcased a range of state-of-the-art software solutions for establishing an end-to-end DtP data flow. Nevertheless, there are still several challenges that need to be solved accordingly.

First, the overall low adoption rate of AEC specific human-robot-work simulations for production in connection with BIM-related approaches is an eminently occurring challenge and derived from interoperability issues (e.g. IFC) because certain software solutions missing essential capabilities to process construction industry specific file formats (e.g. IFC, including geometry and semantics).

Moreover, this challenge is additionally exacerbated by a lack of data preparation and agglomeration to enable a better-informed and thereby more efficient or seamless digital workflow. This issue can cause correction loops, redundancies and thereby delays, as well as cost overruns [19].

Despite the BIM-approach with correlating IFC-schema as an attempt to standardize data flow throughout the design phases, there are still different file formats needed/used (e.g. STEP, cpiXML, LandXML etc.) to initiate analyses, simulations, or machine controls due to their proprietary nature, as well as data schema.

Furthermore, the current BIM-approach in combination with consecutive robot control for production is still not sufficient due to the lack of production-relevant data preparation, as well as insufficient consideration of ergonomic standards and human abilities for human-robot-collaboration (HRC) [20]. This can lead to expensive corrections loops and health and safety related risks. A better consideration of human human-robot-work-process could support the development of appropriate work processes. That is why a more detailed production-, as well as human-centered work process data level description is required.

3 DtP-workflow

3.1 General digital workflow and information management

The proposed DtP-workflow is showcased in Figure 1 and focuses on the software layer, which can be divided into three sequential processes. In this regard, the accumulated information derived from each step is transferred through a data exchange following a BIM-based approach (IFC schema). In the CAD-processes (construction perspective) the design intent documentation of the client is getting processed with the aim to provide product level information which describes a product in accordance to the clients requirements for the consecutive Computer Aided Engineering (CAE) processes incorporating a first virtual product model. Product model information thereby consists of geometric (e.g. solids, surfaces etc.) and semantic (e.g. unit-based dimensions, materials, physical properties, mass, product cost etc.) data.

The CAD-processes are followed by the CAE-processes (production perspective) where the product is further detailed in terms of its elements. Furthermore, the related production system is planned, as well as consecutively simulated, analyzed, and optimized in accordance with the elements. The resulting element level information also consists of geometric (e.g. detailing, element aggregations etc.) and semantic (e.g. processes, assembly instructions, production cost, health and safety related information etc.) data.

Afterwards, the prepared and accumulated data (element level information) is processed in the Computer Aided Manufacturing (CAM) processes and used for initiating machine control with correlating simulations, analyses, as well as optimizations. The CAM-processes thereby transfer the implicit assembly instructions of the element level information into explicit ones and eventually generating machine code (production documentation) for production. Furthermore, the CAM-processes utilizes the relevant production level information to generate a better-informed machine control.

This sequential data preparation and agglomeration is consistently processed throughout the CAx processes due to the introduced data exchange layer which allows interoperability accordingly. This data exchange layer is further elaborated in section 3.3.

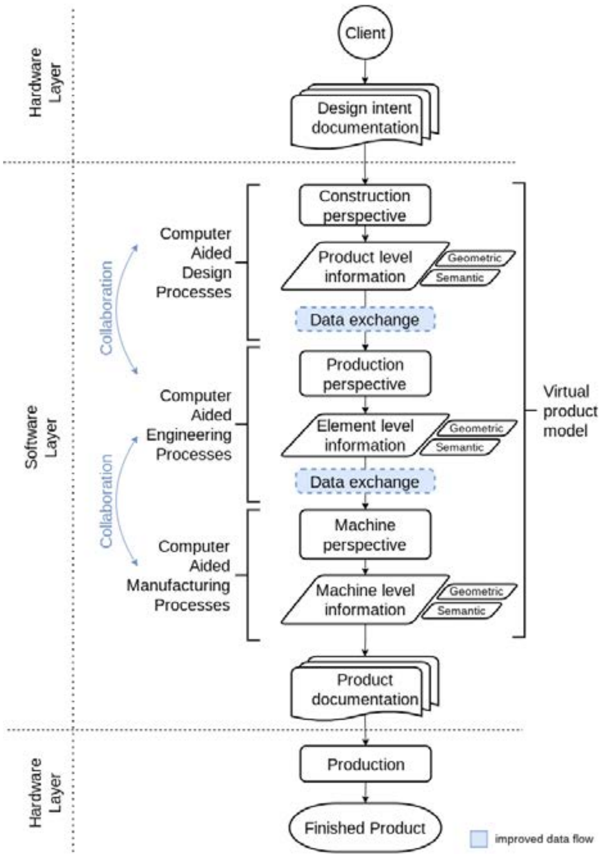

Figure 1: General digital workflow and information management of the DtP-workflow.

3.2 Collaboration loops

Each CAx process has its own collaboration and thereby development loop (Figure 2), where the current process state is reviewed based on the objectives. In case these objectives are not met, the origin of the given issue is determined. If the issue is related to the previous process, proper documentation is created and is handed to the previous process. Otherwise, the loop does not leave the scope of the current process.

In this regard, an integral part of the applied BIM-approach is the utilization of established exchange mechanisms as described in section 2.1.1 - namely MVD for the definition of the actual exchange - BCF for handling model-based issue management between the top-level process steps and the IFC for the persistent storage of model and process data.

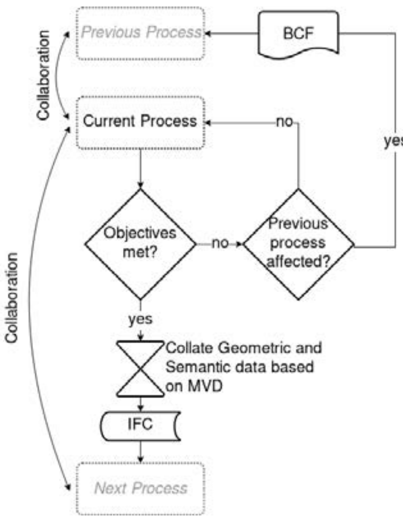

Figure 2: General collaboration loops within the CAx processes.

3.3 Idealistic data exchange

The integrated BIM-based data flow facilitates the proposed DtP-workflow with the underlying digital workflow (section 3.1). This calls for a common data format - namely IFC - which serves as a data storage for all related CAx process related information (geometric and semantic data). In Figure 3 the BIM-based data flow is shown accordingly.

If the user wants to push IFC data to the IFC data storage, the prepared and accumulated IFC data can be integrated via an import data routine.

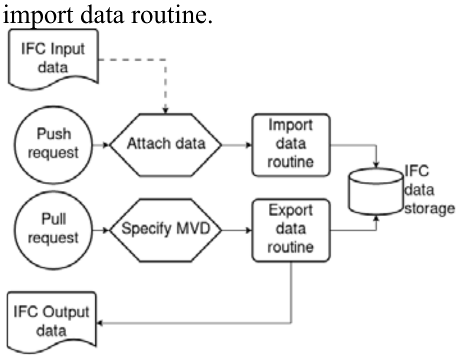

Figure 3: Idealistic data exchange.

If the user wants to pull IFC data from the IFC data storage a pull request can be issued through the specification of a desired MVD and the subsequent export routine delivers the related output IFC file.

4 Use-case

4.1 Production process

The production process describes the manufacturing and assembly of the balcony platform (Figure 4). In this context, the balcony platform (Figure 4, outlined in red) is assembled from various elements: edge profiles, platform beams and segments, as well as connectors and vary in dimensions from 1x1m to 7x3m.

In the general production process – used for all iterations - the edge profiles (Figure 4, dark grey) are first connected using profiled corner connectors (Figure 4, light grey) and bolts. The platform beams (Figure 4, medium grey) and segments must be glued, sealed, and riveted together after they have been inserted accordingly. Further elements (e.g. railing etc.) are attached in downstream processes.

Figure 4: Balcony and platform for the production process (software: Blender BIM).

4.2 Digital workflow in according to the DtP-workflow

The following testing of the DtP-workflow is executed in accordance to the previously introduced general digital workflow and information management (Figure 1).

The desired product is firstly designed by correlating CAD software with BIM-authoring capabilities (e.g. Autodesk Revit, Blender BIM etc.) and afterwards prepared and accumulated with relevant product level information, for example in this case: overall geometry of the balcony and semantics regarding visual and structural boundary conditions (e.g.. location, surface finishes, mounting systems etc.).

Subsequently, the resulting virtual product model can be seamlessly handed over to the CAE processes due to the developed data exchange layer (section 4.3), where the given product level information is further complemented with information at the element level. For the balcony, this includes, but is not limited to designing and considering further geometry of the profiles and semantics (e.g. weights/mass, center of gravity, bearing load etc.).

In order to determine further semantic element level information of the production process (e.g. human-robot-interaction, ergonomics, task allocations etc.) and the corresponding optimization, simulation software with DHM (in this case emaWD) is used accordingly.

This simulation software is used to orchestrate the previously described elements within the production context (e.g. production line etc.). Therefore, emaWD utilizes the following element level information established by the preceding processes: Element-Identifier, Element-Name, Dimension (e.g. Length, Width, Height) and Weight.

In this use-case three different production process variants were modeled (initial, variant 1, variant 2) in order to assess the capabilities of the DtP-workflow regarding scalability, since each iteration augments the processes and thereby increasing the complexity.

Initially the balcony platform (4x2m) is produced in a manual process (Figure 5) only by humans and characterized by a large number of elements, ergonomically unfavorable work conditions due to long, bulky parts (e.g. up to 4m long), as well as high element weights (e.g. between 3 and 12kg) and very repetitive work processes (e.g. gluing, riveting, pick and place etc.).

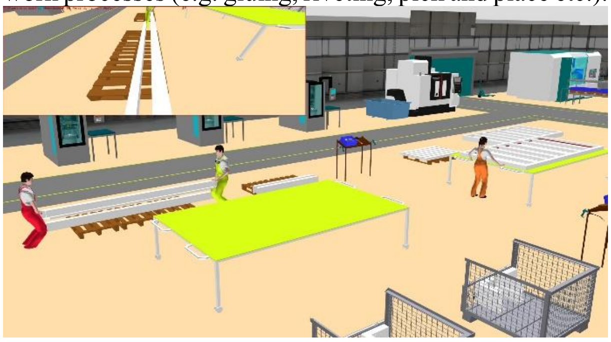

Figure 5: Initial production process (software: emaWD).

The first iteration (Figure 6) incorporates the modification of the pick-up height, replacing the euro pallets with elevated racks as well as utilizing a dedicated lifting table and pallet cages. This in turn resulted in an improvement regarding ergonomic and production criteria (e.g. ergonomic assessment EAWS, execution time etc.).

Figure 6: Optimized production process variant 1 (software: emaWD).

In the second variant (Figure 7), the handling of the segments of the outer frame is carried out by a robot (KUKA KR16-2). This leads to further optimization regarding the detailed ergonomic assessment and leading time. In this regard, a previously developed implementation [18] was used, which enhances robotic simulation functionalities (more realistic robot behaviour model for robot specific tasks derived from ROS-based simulation packages and enabled by data exchange) in emaWD. The use of this developed implementation assures a better simulation result due to more accurate collision-free trajectory planning capabilities taking environmental objects into account.

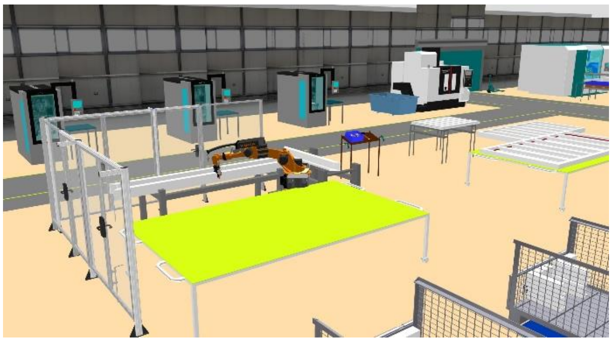

Figure 7: Optimized production process variant 2 (software: emaWD).

Afterwards the optimized robotic movements (assembly instructions) were transferred (data exchange, section 4.3) to the CAM processes in which the element level information is further complemented with machine level information. In this process the further prepared and accumulated data is utilized to introduce a machine/robot control.

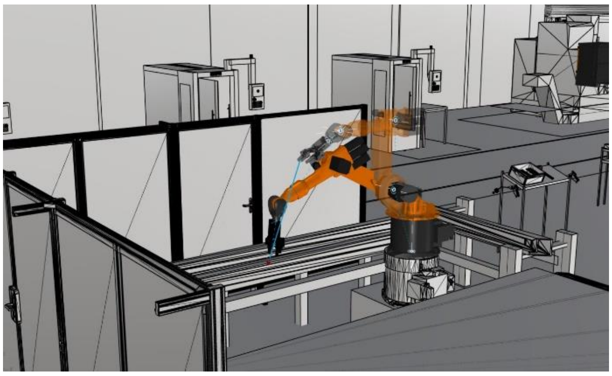

Figure 8: Optimized production process variant 2 and initiated machine/robot control (software: HAL Robotics Framework).

Previous data can be fed into the corresponding data compartments (record) in a machine simulation and control software solution (Figure 8, HAL Robotics Framework). Afterwards the machine code can be uploaded or exported to the robot controller in the joint space (programmable logic controller, PLC) to enable the production accordingly.

4.3 Applied data flow

With the use-case (balcony pre-assembly) we show the prototypically BIM-based DtP-workflow enabled by programmed IFC semantic parsers (leveraging IfcOpenShell) which translate a CSV or XML file to a software readable format assuring previously aggregated data is transmitted seamlessly.

The introduction of this layer is thereby bridging the interoperability gap and being able to extract and integrate various structured (e.g. tabular, hierarchical etc.) data formats expected by the used software solutions. The impact on the proposed data exchange (Figure 3) is shown in Figure 9.

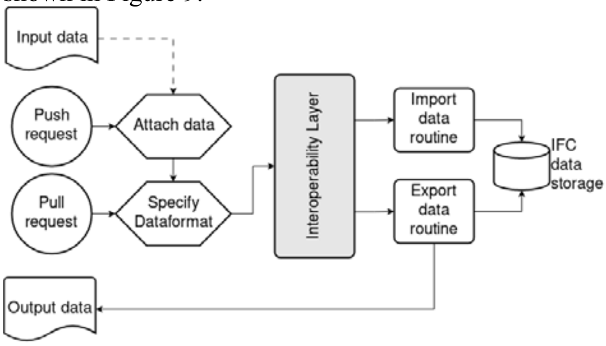

Figure 9: Applied data flow.

5 Results

The described use-case indicates several benefits as well as issues regarding the proposed DtP-workflow.

The application of a collaborative, model-based data exchange led to a reduction in planning effort. Less time was needed to integrate the element-level information from the handed over IFC file into the simulation software (emaWD). Additionally, the model-based approach facilitated communication as well as end-to-end data flow capabilities and thereby further supplementing the overall planning processes. Through reducing the effort in preparation for interfacing between software solutions and corresponding data agglomeration, a reduction in overall susceptibility for failures could be achieved. The usage of human-robot-work-process simulation software (emaWD) in the context of the AEC industry could therefore significantly support in the related tasks by identifying and quantifying risks.

6 Discussion

The proposed DtP-workflow is still at a prototypical stage and more research needs to be conducted in this direction.

In future research the proposed DtP-workflow needs to be tested for several use-cases (especially an on-site AEC-industry related use-case, not only for a prefabrication use-case), as well as evaluated under real-life production conditions. Additionally, a more detailed DtP-workflow-related stakeholder allocation needs to be conducted. The current state of the developed data exchange layer (section 4.3) relies on a MVD as a means of concurrent data exchange, lacking the description of a schema-based, standardized way of data integrity verification [21]. This could be resolved by utilizing or introducing more specific IFC classes for creating the semantic context in a DtP-workflow (section 3.3).

In addition, there are technical challenges involved when dealing with optimizing data flow utilizing the IFC data schema such as efficiently processing large and complex data, detecting and resolving semantic errors or inconsistencies and ensuring compatibility. These challenges have to be considered accordingly.

In the end the workflow was developed with the intent to perform the data flow automatically. However, a completely automated implementation was considered beyond the scope of the conducted research as it necessitates the extension of proprietary software Application Programming Interfaces (APIs). Therefore, the workflow majorly showcases a solution for solving aforementioned issues without disrupting the underlying software architectures. In addition, the workflow could be used for further developments towards linking different software solutions in the AEC industry.

7 Conclusions

There is still the potential to reduce cost, save time and simultaneously assure quality in modern AEC-related digital workflows. This was demonstrated by enabling human-robot-work process software solutions (emaWD) to utilize and accelerate tasks, based on the DtP-workflow with a derived digital workflow in a BIM-based holistic manner (IFC schema). Thereby data preparation, agglomeration and interfacing software solution capabilities can be alleviated.

With the described combination of BIM, human-robot-work process simulation and consecutive machine control, a virtual product model was prototypically developed from design to production.

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