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Requirements for Modeling Frameworks in the Context of Assembly Work Instruction Development

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Abstract

This paper introduces requirements for a flexible modeling framework for creating digital work instructions (DWI) for industrial assembly processes. Designed to standardize DWI development, the framework organizes materials, tools, and hints into structured workflows, integrating diverse input data. Developed through a three-phase methodology – data identification, framework creation, and validation – its design is informed by a requirement analysis. A LEGO® use case demonstrates its application, highlighting its potential to improve efficiency, reduce errors, and support the integration of advanced technologies in manufacturing.

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1. Introduction

The shift from traditional paper-based work instructions to digital formats marks a significant transformation in modern manufacturing. As industries embrace digitalization, the demand for standardized, adaptable, and easily accessible digital work instructions (DWIs) has grown. Particularly in manual assembly, DWIs offer a dynamic and responsive interface that helps address challenges such as process variability, frequent design changes, and worker training [1]. However, despite their advantages, existing DWI systems often struggle with standardization, interoperability, and efficient integration into engineering and production workflows. Recent literature highlights the need for structured, systematic approaches to developing and managing DWIs [2,3]. To bridge this gap, this paper proposes a modeling framework that leverages engineering design principles to create a structured, modular approach for developing DWIs. By incorporating methodologies from model-based systems engineering, knowledge-based engineering, and digital twin technologies, the framework enhances efficiency, error reduction, and integration with advanced manufacturing technologies, such as computer vision and robotics. The structured approach enables seamless data flow between design and manufacturing, allowing for the automated generation of assembly instructions from CAD models [4]. Additionally, it supports design iteration and variant management, which are crucial in industries with high product customization and rapid development cycles. The framework follows the structured methodology outlined by McMeekin et al. [5], which identifies three key phases in the creation of methodological frameworks:

1. Identifying relevant data,
2. Developing the framework, and
3. Validating and refining the framework.

This paper primarily addresses phases 1 and 2, focusing on identifying essential data structures and formulating a

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standardized framework. A preliminary exploration of phase 3 is conducted through a requirement analysis transfer, with further validation planned for future research. By formalizing the structure of DWIs through engineering design principles, this work contributes to advancing design-for-assembly methodologies, supporting the next generation of intelligent and adaptive manufacturing processes.

2. State of the Art

Technological advances have shaped the evolution of assembly DWI. Contemporary frameworks employ a range of methodologies, including augmented reality (AR), virtual reality (VR), and DWI. Knowledge Graph-Based AR frameworks enhance the assembly process [6]. They integrate assembly process information with AR visualization, allowing workers to see superimposed instructions and relevant data in real time. Integrating XML or JSON file export helps describe assembly steps in visualization formats and create more accessible and intuitive instructions [7,8]. Modern DWI frameworks often integrate CAD systems, allowing interactive 3D renderings and automated assembly sequence generation [4]. This integration enhances the preparation process, enabling better planning and execution of assembly tasks [4]. Recent methodologies explore using VR tools to rationalize manufacturing processes, particularly during pre-production. Companies can streamline training and improve understanding of complex assembly tasks by employing video, AR, and VR tutorials. This approach has been validated through real-world implementations, demonstrating its effectiveness in enhancing process execution [9]. Research also focuses on integrating computer vision and deep learning methods to automate the localization and orientation of non-rigid objects in 3D scenes during assembly. An automated quality check is possible by determining assembly objects. This aims to reduce human workload and improve efficiency in assembly tasks [10,11].

Leder et al. [2] present a framework for designing quality-centered assistance systems tailored to smart factories, addressing the gap in real-time quality assessment within manufacturing processes. They comprise two phases: Preparation and Execution. Evaluated through a use case in the aerospace industry and an expert questionnaire, the framework received positive feedback, highlighting its potential to enhance quality assurance while suggesting further refinements for practical implementation. While Leder et al. [2] developed a framework for designing quality-centered assistance systems, including a workflow editor, this paper takes a different focus. Building upon [2], it emphasizes a broader approach to creating process chains. Although quality parameters can still be incorporated, this paper extends beyond them by introducing a more generalized set of parameters. Additionally, technical resources such as tools and materials are now integral components of the processes and are expanded to include various parameters.

3. Requirement Analysis

The requirements were derived from product development, assembly planning, framework creation, and computer science literature. References to each requirement are given as examples. By addressing these requirements, a framework can be established that supports the development of an effective workflow editor tailored for assembly DWIs.

Structure and Organization. A clear structure in assembly planning significantly reduces complexity and improves organization. Guidelines and standards help streamline the planning process and ensure consistency [12].

Reusability and Modularity. Integrating reusable and modular components in assembly planning optimizes resource allocation and expedites the deployment of assembly processes. This approach encourages the creation of reusable code, which is essential for reducing development and maintenance costs [13].

Collaboration. Frameworks promote collaboration between teams or departments by establishing common standards and protocols. This ensures all parties are aligned and working towards the same goals, improving efficiency and reducing conflicts [14].

Standardization. Standardizing processes increases consistency and improves quality across organizational workflows. It facilitates compliance with regulations and ensures that best practices are followed consistently throughout the assembly planning process [15].

Efficiency. By automating or simplifying common tasks, frameworks promote efficient workflows. This increases efficiency by higher productivity and resource savings in the assembly process [16].

Flexibility and Adaptability. Flexibility in assembly planning allows customization and adaptation to specific assembly needs without requiring a complete redesign of the entire structure [14].

Integration. Integration with other technologies or systems increases interoperability within the production ecosystem. This improves overall efficiency and allows seamless communication between different stages of the production process [13].

Error Reduction. Clear guidelines, standards, and best practices in assembly planning help minimize common errors. This improves product quality and reduces rework or corrections during assembly [12].

Documentation and Education. Comprehensive documentation and training in assembly planning support user education, ensuring new team members are accommodated quickly, reducing training time, and improving team performance [13].

Sustainability. Integrating sustainability into assembly planning creates maintainable solutions that minimize environmental impact. This benefits the environment and can lead to more efficient use of resources [12].

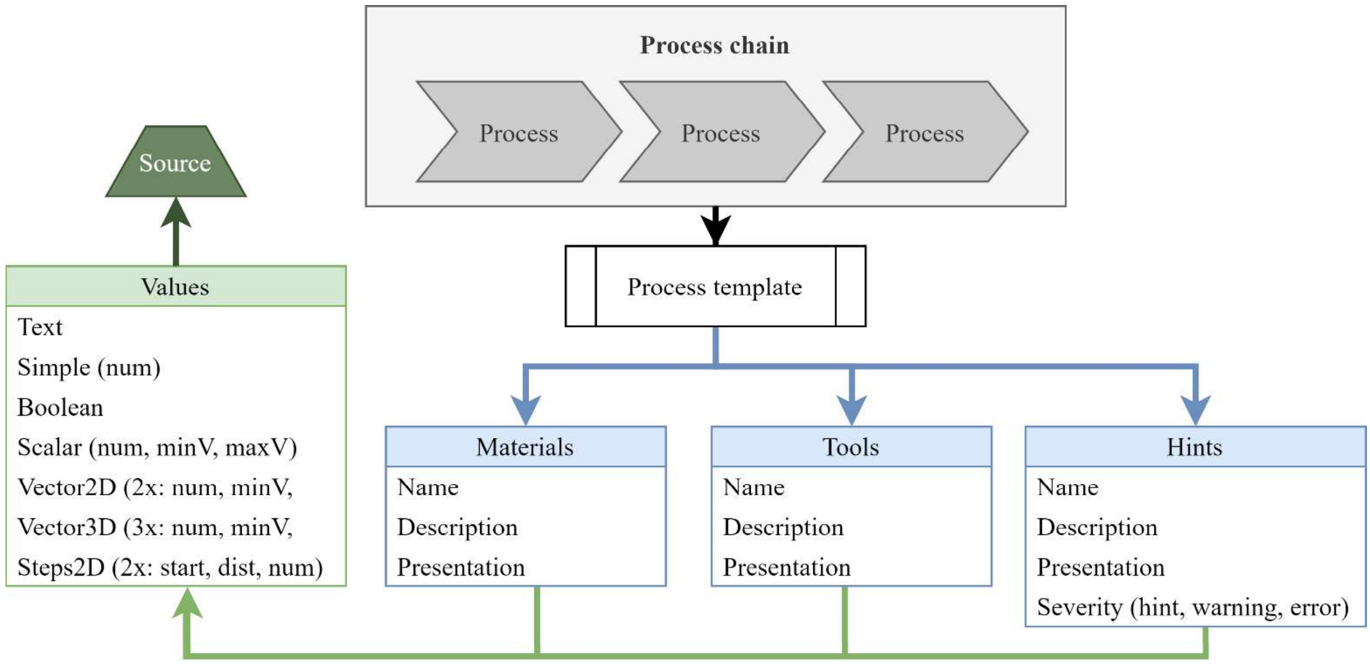

Figure 1: Modeling framework for the development of assembly work instructions with blue the main components of a process and green the corresponding parameters for each process or component.

4. Modeling Framework

The modeling framework was developed by considering the requirements, and it facilitates the integration of various description data (values) into a structured workflow (process chain). By adding these values into a process template, the framework allows customization and control over the materials, tools, and hints required for executing the processes. This framework is based on Leder et al. [3], who defined process chains using modular standard elements. While these elements were limited to the manufacturing techniques of riveting, drilling, crimping, cleaning, and drawing, the standard elements in the proposed framework (process template) are unlimited, ranging from empty to highly specialized process templates.

Figure 1 represents the framework for a template-based process chain where the input values are integrated into different aspects of a process. This framework focuses on structuring processes, tools, materials, and feedback (hints) for a system to create assembly process chains.

4.1. Process Chain

The process chain represents a set of DWIs for assembly. It consists of several process steps based on different process templates with individual values and process-based parameters.

Process template. A process template is pre-defined with specific materials, tools, and hints. Here, only empty values are defined and are filled with process-specific parameters when creating the process chain. For general processes, an empty template can be made. An example process is *screwing*. The process is based on a template with the material of a screwdriver and a drill bit. Also, the hints to check the correct screw size and type and drill bit size, as well as the warning of the torque, are already defined in the template. Figure 2 illustrates the example of the screwing process template. For a specific screw process, the screwdriver can be exchanged with, e.g., a particular piston screwdriver and the drill bit size can have a size of, e.g., 2. Additionally, the correct screw type and size can be replaced.

4.2. Materials, Tools, and Hints

The framework's key components are materials, tools, and hints. They are the basis and represent all elements needed for assembly processes.

Materials. The materials describe all materials needed for assembly. Their data structure always has a name and, in addition, can have a description. Also, a presentation, like an image or a how-to-use video, can be added. Examples of materials are Allen screws with different amounts, sizes, and lengths defined by the values, driving disks, or perforated plates.

Tools. Tools are often needed to process the materials. The tools class defines these tools and requires a name, an optional description, and an optional presentation. Screwdrivers and bits of different sizes are examples of tools.

Hints. Hints are no physical elements but rather input for assistance systems. They need a name as well, can have a description and a presentation (for informational assistance systems), and, in addition, need a severity. The severity defines whether the item is a hint, a warning, or an error. A hint is general information about a process step. A warning can also be general information, but also a result of a value check of, e.g., an inadequate posture while assembling. An error results from a value check, like a wrong drill bit size or an incorrect material positioning on another component.

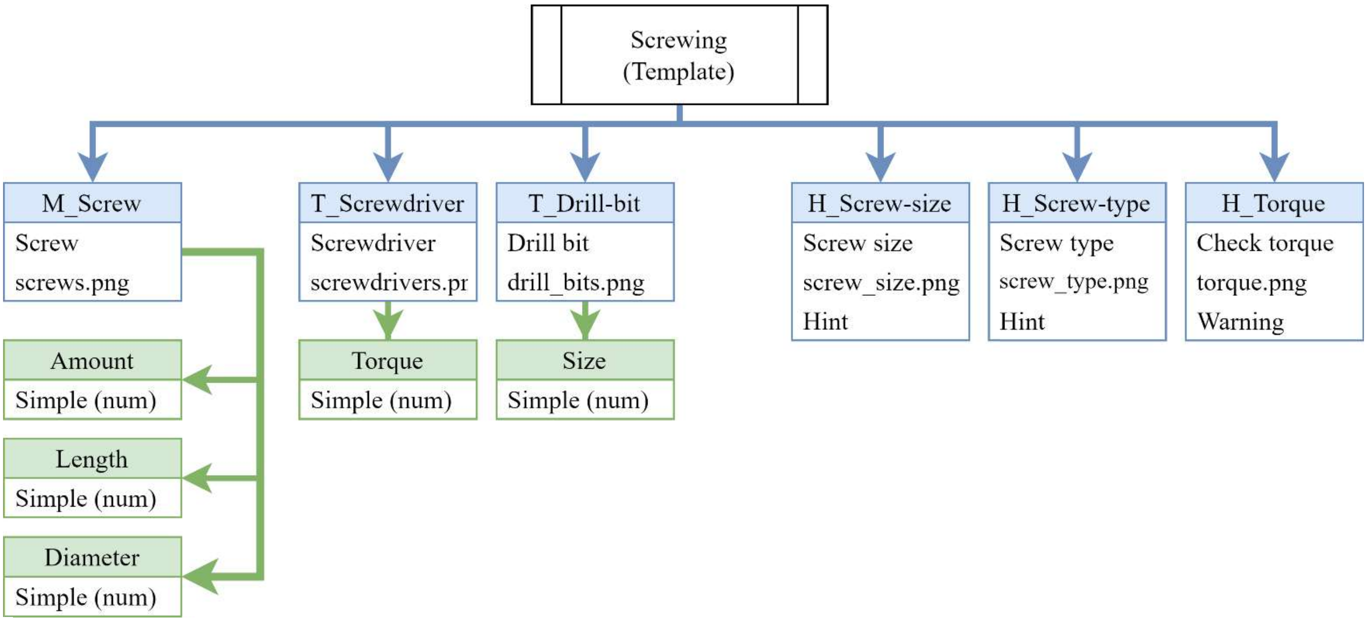

Figure 2: Example of a template process for screwing.

4.3. Values

In contrast to Leder et al. [2], this modeling framework is more generalized, especially in the values. The values are most important in this framework, as they define all aspects of checkable data. The following data types exist: Text, Simple, Boolean, Scalar, Vector2D, Vector3D, and Steps2D.

Text. Text values can be all kinds of texts, like alternations of the description, non-numerical serial numbers, color descriptions, or material orientation.

Simple. Simple values are number values and can be used for, e.g., numerical serial numbers, Inclination, amount of side knobs, or length.

Boolean. A boolean value can describe general parameters for similar workpieces, such as whether it has corners, is round, is reinforced, or has an axle bore.

Scalar. The scalar value defines a single target value with its minimum and maximum values, e.g., a range for the size of screws or tolerances for a drilling hole.

Vector 2D and Vector 3D. Vector2Ds and vector3Ds are based on the scalar value but can be used to describe parameters in a two or three-dimensional space, like the dimensions of materials or a workpiece.

Steps2D. Lastly, the Steps2d can represent repeated values, as it would be with a row of drill holes. Here, the X and Y starting points are defined; from these points, the distance between the drill holes and the overall amount in a row and several columns can be added.

Source. The sources complement the values by addressing external data input and output. Here, links to sensors, other databases, or assistance systems can be added to transfer, e.g., quality or ergonomic parameters and their analysis results.

5. Use Case

A LEGO® assembly process was selected as the use case to evaluate the framework. LEGO® is frequently used in research as a representative example of assembly processes [17] due to its modularity and structured assembly steps. This study chose a specific model - the orange echeveria from the LEGO® succulents series. Each assembly step was carefully defined, including attributes such as step name, description, required materials, tools, media, and additional hints. Figure 3 illustrates an example of the first step.

In this process, various data types were assigned to the components. For instance, the ground plate's material was represented as a **Vector2D (dimension)**, while other attributes, like **serial number** and **amount**, were stored as **simple numerical values**. The **color** was encoded as **textual information**. For the cone, additional parameters were defined, including a **boolean** indicating the presence of an upper groove. The framework also integrates external validation mechanisms, such as an assistance system, to verify component placement. In this case, a server address is linked, enabling commands to check, for example, whether an image of the ground plate matches the expected size.

A key advantage of the proposed framework is its modularity and adaptability, which allow for precise modeling of LEGO® components and efficient handling of variations. LEGO® plates, for example, exist in multiple forms and sizes, ranging from small (2×2) to substantial (30×30) and featuring different edge geometries - either sharp-edged or rounded. The framework standardizes these variations, ensuring consistency while maintaining flexibility. Supporting reusable instances allows efficient adaptation to different component variants without redundant definitions, thereby streamlining the process of managing diverse LEGO® blocks in assembly workflows.

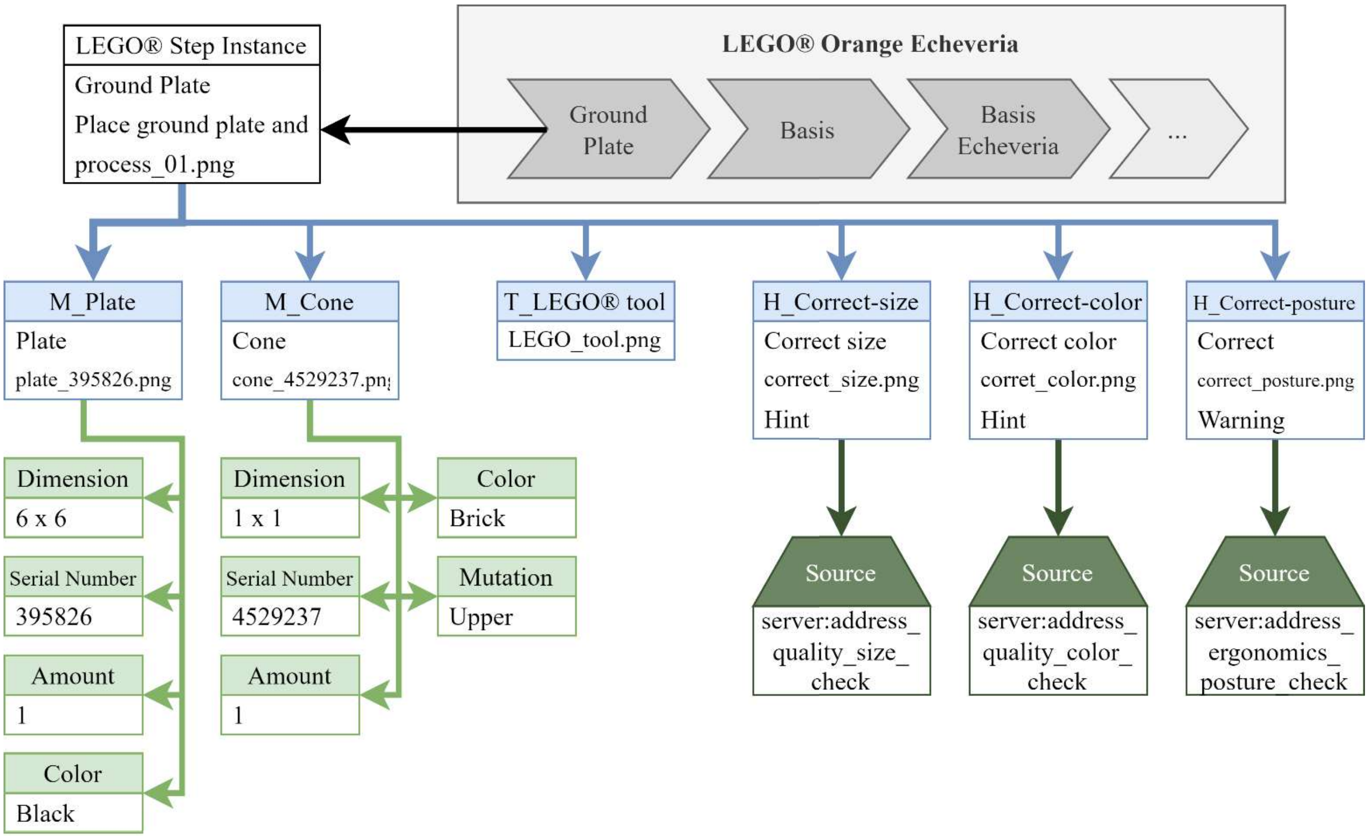

Figure 3: LEGO® use case to evaluate the framework.

6. Discussion

The modeling framework has been designed according to the principles of class diagrams to establish a standardized approach that enhances the efficiency and collaboration of DWI creation. By creating reusable values and process templates, the framework enables general and repetitive processes, thus allowing for modulation in the concluding steps without necessitating repetitive data entry. The standardization process facilitates the data input to create process chains, enhancing efficiency. The components operate in a manner analogous to classes in software development, thereby promoting flexibility and adaptability. Consequently, the framework can be integrated seamlessly into a workflow editor, expediting development through pre-defined data structures that influence user interface design. This rapid adaptability accelerates time-to-market and facilitates integration with other systems, such as informational assistance systems and advanced technologies like computer vision or deep learning. The predefined hints, values, and sources within the framework reduce errors by establishing a straightforward process for creating assembly DWIs, wherein general values guide process templates. The framework's adherence to software development principles ensures high maintainability and efficiency.

Besides, the framework still needs to focus on assembly priority graphs, though implementing those should be easy, as it implements the processes and adds sub-processes. In addition, machine parameters are not considered as single instances within the framework, as the framework addresses (manual) assembly processes. This could also quickly be resolved by defining a machine as a tool, adding control parameters, or expanding the critical components by a machine class. Lastly, the framework does not include robotic integration. However, the framework's flexibility makes adding particular robotic values as their classes possible, deriving from the value definition.

7. Conclusion and Future Work

This paper introduced a modeling framework designed to optimize the creation of assembly work instructions (WIs) by leveraging structured principles from software development, such as class diagrams. The framework provides a modular and adaptable structure that enhances efficiency, standardization, and collaboration. Reducing redundancy through reusable templates and values streamlines the generation of WIs while maintaining flexibility for customization and integration with external systems. The successful application of this approach to a LEGO® assembly use case demonstrates its feasibility and potential scalability in more complex industrial scenarios. Beyond assembly WIs, the framework has broader implications for digital manufacturing and Industry 4.0 initiatives. Its structured nature makes it well-suited for integration with intelligent assistance systems, such as AR guidance, automated quality control, or AI-driven process optimization. Additionally, by formalizing assembly instructions into a structured digital format, the framework could contribute to more automated knowledge transfer, improving training procedures for human workers and facilitating human-robot collaboration in hybrid manufacturing environments.

Future work will focus on the limitations and expanding the framework's capabilities. Integrating assembly priority graphs will enhance the modeling of complex, interdependent workflows. Additionally, incorporating machine parameters and robotic integration will allow the framework to support (semi-)automated assembly processes. Exploring AI-driven process optimization, data-driven adaptation of WIs, and real-time validation mechanisms could further enhance its utility. Finally, broader validation across diverse industrial applications will be conducted to assess the framework's robustness and adaptability. By continuing this development, the framework has the potential to serve as a foundational tool for the next generation of intelligent, adaptable manufacturing processes, bridging the gap between traditional assembly documentation and intelligent, data-driven production environments.

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