Automatic Generation of Digital Twin Models for Simulation of Reconfigurable Robotic Fabrication Systems for Timber Prefabrication

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Abstract -

Timber construction and prefabrication are becoming increasingly important in the building and construction industry. The degree of automation in this area is low. Caused by the great variability of construction projects and building components, automation systems that can adapt flexibly to different construction projects are required. However, a system that fulfills these conditions does not yet exist. Downtimes for reconfiguration in between projects must be short. The use of robotics for the automation of prefabrication is constantly developing. Recent publications present a novel, flexible, reconfigurable, and transportable manufacturing platform using industrial robots. A system consisting of several of these modular platforms can be flexibly adapted to the changing requirements of different construction projects and set up on-site at local timber construction companies. To ensure the manufacturability of the timber components and to minimize downtimes between projects, the entire workflow from digital design to fabrication must be considered. The co-design approach makes this possible. It breaks up the currently existing sequential process from design to fabrication and considers all sub-steps holistically. Thus, enabling the consideration of the fabrication capabilities during building design. This allows the planning of building components and system layout so that fabrication is feasible. To achieve this, the fabricability of a given system layout has to be evaluated. This requires a digital twin of the fabrication system as a simulation model. The reconfigurability of the fabrication system must be reflected by the digital twin. The fabrication tasks and the system configuration are constantly changed in search of a valid combination. Therefore, with each iteration, the digital twin must be adapted or newly created. At present, this is mostly a manual process. This makes the whole approach unfeasible. To solve this problem, this work presents an approach for the automated, model-based generation of digital twins for the simulation of reconfigurable fabrication systems for timber prefabrication.

Keywords -

Timber Prefabrication, Digital Twin, Cyber-Physical System, Software Defined Manufacturing, Simulation

1 Introduction

The use of wood as a sustainable building material can help to reduce the emission of greenhouse gases from the construction industry [1]. In terms of recycling, wood as a building material also offers important advantages over building with mineral materials [2]. Prefabrication promises to at least partially solve current problems such as the high demand for affordable housing. The construction industry currently has lower productivity and degree of automation than the manufacturing industry. This important industry currently still relies strongly on the use of manual labor [3]. Certain branches of timber construction have already successfully adopted approaches from manufacturing [4]. However, this highly automated branch of timber construction is found almost exclusively in residential housing and accounts for only a very small share of the overall construction industry market [5]. The major part of timber construction has a strong project-based orientation [6]. Most projects are to some extent unique.

The mostly small [7] and locally based companies have to adapt flexibly from project to project and hence need flexible fabrication systems. Downtime between projects must be short. The wide variability of building components due to location-specific building codes and the strong dependence of the building design on the specific building location and the client is a challenge [8]. The wide variance in the requirements of project-based construction poses currently unsolved challenges for small and medium-sized timber construction companies in terms of automation. This is especially true for more advanced, higher-performance lightweight construction systems that use fewer resources but require more complex fabrication processes and higher fabrication accuracies. Existing automation solutions in timber construction are very inflexible. These often highly automated systems can be configured from a modular component system. However, later adaptations of these machines to specific project requirements are hardly possible.

1.1 Adaptive Fabrication Systems

Due to the lower requirements on machining accuracy compared to manufacturing technology, especially in subtractive machining, the use of industrial robots has become established in timber prefabrication [9]. Industrial robots offer the necessary flexibility that timber prefabrication requires [10]. Furthermore, the performance of industrial robots is sufficient for most timber building components with lower demands on machining accuracy and surface quality. Recent examples of the use of industrial robots in construction are the assembly of single timber frames [11] or the construction of successive roofs using ceiling-mounted industrial robots [12]. On the one hand, these examples show the potential for automating highly complex timber prefabrication tasks with industrial robots. On the other hand, these systems were developed specifically for this particular task and are not flexibly adaptable to other tasks.

In [8], a novel approach to the automation of timber prefabrication was presented using a modular, reconfigurable and transportable platform that was used to fabricate the building demonstrator from [6]. The platform is equipped with end-effectors for milling, nailing, gluing, and handling components.

A system consisting of several such platforms can be adapted to the specific requirements of individual construction projects by the arrangement and number of modules as well as their configuration. Since these modules are transportable, the fabrication system can be set up on-site at local timber construction companies.

1.2 Fabrication Planning and Simulation

Such a modular, reconfigurable fabrication system can be equipped with different tools and effectors as required. The system layout can be reconfigured by rearranging and replacing the system modules. To ensure minimal downtime between projects, this must be achievable in a short time and with minimal effort.

Several aspects play an important role in the operation and the successful, fast reconfiguration of such a fabrication system. A suitable control system is needed to operate the fabrication system. The adaptation of the control to a given system layout must be simple and as automated as possible. The same applies to the calibration of the modular system after a reconfiguration of the modules. Another important aspect is the planning of the layout and the transfer of the building design to the fabrication. To keep downtimes low, both the fabrication process and the system layout must be pre-planned and pre-validated. To efficiently ensure the manufacturability of the components with the existing fabrication capabilities that are available in the given fabrication setup, the usual sequential workflow from design to engineering to fabrication needs to be broken down. One such method is co-design [13]. In co-design, all involved stakeholders work in parallel and not sequentially. Their planning and calculation models interact via defined interfaces. The objective is to integrate manufacturability and machine skills into the design and planning process.

This can be done in parts on an abstract level, considering the workspaces, the payloads, and the manufacturing processes of the modules. Following on from this, the fabrication of the components must be simulated in detail. This requires a simulation model of the fabrication system. To reliably validate the manufacturability for a given system layout and task schedule, and thus to enable fast reconfiguration between projects, the simulation model must cover all relevant factors, such as path planning and execution, collisions, or reachability. This requires a digital twin of the entire fabrication system, which also includes the control system and incorporates it into the simulation. In this way, the later task execution can be pre-validated before the actual reconfiguration of the plant. To enable the rapid simulation of different system layouts and task schedules, a method that automatically generates the simulation models for a given system layout and manages the entire simulation process is needed. This paper presents the concept and early implementation of a method for automatic model generation and execution of digital twin models of the above described reconfigurable fabrication system for timber prefabrication. The concept is validated based on a simulation with different fabrication layouts and a simple tasks sequence.

The remainder of this paper is organized as follows. Section 2 discusses related work in the field of digital twins in manufacturing and construction technology. In Section 3, we discuss the problem definition and present our solution approach. This is followed by Section 4, where we describe the current state of implementation. The presented method is validated in section 5 We conclude and discuss our work in Section 6.

2 Related Work

Different definitions of digital twins are known in the literature. A general definition has been established by NASA as an "integrated multi-physics, multi-scale, probabilistic as-is simulation of a product, system, or process that can reflect the lifetime of the corresponding twin using available physical models, historical data, and real-time data" [14]. In principle, digital twins can be divided into online and offline digital twins. Online digital twins run in parallel with the system. These are used, for example, for the measurement of hard-to-measure conditions , predictive maintenance or life-cycle management . Offline digital twins run independently of the physical system.

Use cases include simulation or planning .

2.1 Digital Twin in Manufacturing and Construction

Different definitions of digital twins are used in manufacturing technology. It can be a virtual image of products, individual machines or machine components or even represent entire plants and factories. Depending on the application, these differ in the level of detail in which the physical instance is mapped. In manufacturing technology, the digital twin is often a model of a system or machine in which, in addition to kinematics and dynamics, communication via fieldbuses is mapped in real-time. In [15] the authors present a digital twin approach that allows the digital twin to be used as an deterministic, real-time environment for the reinforcement learning-based training of an agent for CNC based robotic manipulation of soft-tissue objects. In [16] an approach for real-time co-simulation of digital twin models is presented. In [17], digital twins for online optimization of the real fabrication system are discussed. The authors of [18] present a 3D reconstruction method for the exploration of SME environments with drones. The work of [19] discusses the construction of digital twins employing model-driven approaches. The authors of [20] present a method for the discovery and automatic generation of digital twins. The characteristics of manufacturing systems are derived from data. The authors find that the approach generates models that can correctly estimate the system performance. The work of [21] describes the automatic generation of digital twins for simulation. They use model generation techniques and generate a digital twin of the environment. The authors of [22] use a digital twin to evaluate the reconfiguration of an automation system. They find that their method can reduce reconfiguration times by up to 58%. A modular framework for digital twins of reconfigurable manufacturing systems (RMS) is presented in [23]. The work in [24] applies digital twins of reconfigurable machine tools for design purposes. Studies regarding different kinematics are conducted with the digital twin. The work of [25] presents an approach to reconfiguration planning of RMS based on digital twins. Similarly, the authors of [26] employ a digital twin-driven method for the reconfiguration of manufacturing systems. In [27], the authors discuss digital twin enabled reconfiguration for robotics-based manufacturing systems.

In contrast to manufacturing technology, digital twins in the construction industry are mainly used as a representation of a product like a building component or a building, rather than as a representation of the manufacturing resources used to fabricate it. The authors of [28] state that the use of digital twin technologies offers great potential for the transformation of the construction industry. Applications include structural system integrity, facilities management, monitoring, logistics processes, and energy simulation. In [29], the digital twin of a building including its equipment is used for life cycle management and predictive maintenance. The authors of [30] aim to develop an integrated digital twin that can be used to update building information modeling. In [31], a digital twin is presented as a framework for combining computational design and robotic construction. The digital twin aims to represent the built structure, which is monitored using computer vision techniques. A detailed model of the robot and its behavior beyond its kinematics is not part of the digital twin.

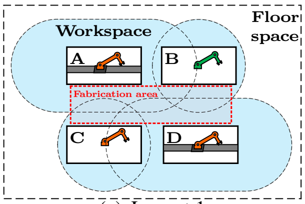
In the field of manufacturing technology, work on the automatic, model-based generation of digital twins is known in the literature. In some cases, there are approaches for system reconfiguration based on digital twins. In the construction industry, digital twins are mainly considered as a model of a building or a construction system. In the field of robotic prefabrication, robot kinematics is used in component design and fabrication planning. However, an actual, automated simulation with the digital twin of the entire manufacturing system with its control system does not take place.

3 Methodology

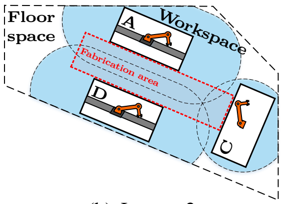
3.1 Problem Formulation

Reconfigurable manufacturing systems offer a high degree of flexibility. However, reconfiguration planning is a very complicated and laborious process. During layout planning, it must be ensured that the resulting system is capable of fabricating the desired parts. This validation is of great importance, as the reconfiguration process involves a lot of time and effort. Since downtimes should be as short as possible, a reconfiguration due to an infeasible layout must be avoided. In the case of the robotic, reconfigurable fabrication system for timber prefabrication described above, further difficulties arise. First, the plant has to be reconfigured relatively frequently from project to project. Second, the system layout and the part geometries have to be planned synchronously so that an optimal combination that satisfies all requirements and constraints is achieved. In addition, the environment constraints change, since the plant is to be set up locally at the timber construction company in each case. Figure 1(a) and Figure 1(b) show examples of different system configurations with different modules and constraints.

The planning and validation of a layout for a given building system must be performed employing a realistic simulation based on a digital twin of the reconfigurable plant, showing an adequate level of detail. Since this is a complex planning problem and the manual creation or adaptation of the simulation models requires a lot of time, a suitable solution for the automated generation of the digital



(a) Layout 1



(b) Layout 2

Figure 1. Examples of Fabrication System Layout

twin is necessary. For each change in the development of the building system, the system layout has to be validated or planned again. The resulting amount of adjustments to the simulation model underline the need for this research.

3.2 Method

To solve the existing problems and hence enable fast, automated validation through simulation we automatically generate and manage the digital twin of the reconfigurable fabrication system. The generation of the digital twins is based on a descriptive model of the system. The level of detail of the digital twin must reflect the relevant behavior of the entire system from task execution to path planning. The 3D geometry, the kinematics, the dynamics, and the system capabilities as well as a description of the control components have to be part of the model. The path tracking behavior of the industrial robot control is excluded and assumed to be ideal. The reason for this is that the industrial robot control is a black box system. Based on a description of the system layout, the digital twin of the entire system is generated. This description holds the module configuration, the system layout with module poses, and the environment. A simulation management component is used to control initialization, simulation execution, and deinitialization of the generated models and enables automatic iteration over different configurations. After a successful start-up of the model, the execution of manufacturing tasks that are defined through a task graph is simulated. After that, the simulation is stopped and deinitialized. The simulation validates reachability, collisions trajectory planning, and task execution. A later extension of the simulation to include process simulation for handling and assembly or subtractive and additive fabrication is being considered and planned.

3.3 Model Structure

The digital twin of the reconfigurable, modular fabrication system is composed of several modules. The individual modules in the form of containers with robots and tools are referred to as fabrication units (FU). These are formed as a combination of the subcomponents platforms, robots, and end effectors. The compatibility of the subcomponents with each other is represented by interface descriptions.

Figure 2 illustrates this concept based on various FUs. The description model of the subcomponents includes not only the interfaces but also the required software components. These are for example responsible for path planning and I/O control. Depending on the tools and robots, CNC components or camera drivers for a simulated camera are also possible. This can be used to derive a dependency tree for the individual FUs or the overall system. As can be seen in Figure 3, each FU has a task controller. This controller is connected to the system controller. The system controller ensures the correct execution of the task schedule described in the graph. As soon as a task can be started, it is sent to the task controller of the corresponding FU, which is then responsible for its execution. In addition to the FUs, the model consists of ENV components that describe the environment, such as the workshop, and OBJ components that represent passive but not static objects. These can be, for example, pallets with material or working tables with components. Existing FUs and their components form a library that can be used for the reconfiguration of FUs and the fabrication system.

3.4 Model Description

Fabrication layouts are described in a text-based way. This description contains a list of FUs that are a part of the component library. For each FU the type and the pose is specified. Furthermore, ENV objects for the environment and OBJ elements for the interaction are included. The digital twin itself is described by XML-based files. These files are generated by the model generator and are started gradually during the ramp-up of the digital twin. They describe all subcomponents of the individual FUs and start them.

3.5 Model Generation

Based on the layout description and the component library, the digital twin is generated by the model generator. The layout description is retrieved and matched with the component library. Based on the FU description the dependency tree can be created. For each FU a Universally Unique Identifier (UUID) is created to uniquely identify the FU. This UUID serves as a prefix for the communication with the module. Identical FUs that occur more than once can thus be uniquely addressed. In a second step, the models of the FUs are adapted to the requirements of the simulation or it is checked whether an adaptation is necessary. Such an adaptation is for example the configuration of the collision monitoring so that occurring collisions can be registered. Furthermore, a bitmask must be generated that defines which collision pairs should not be reported.

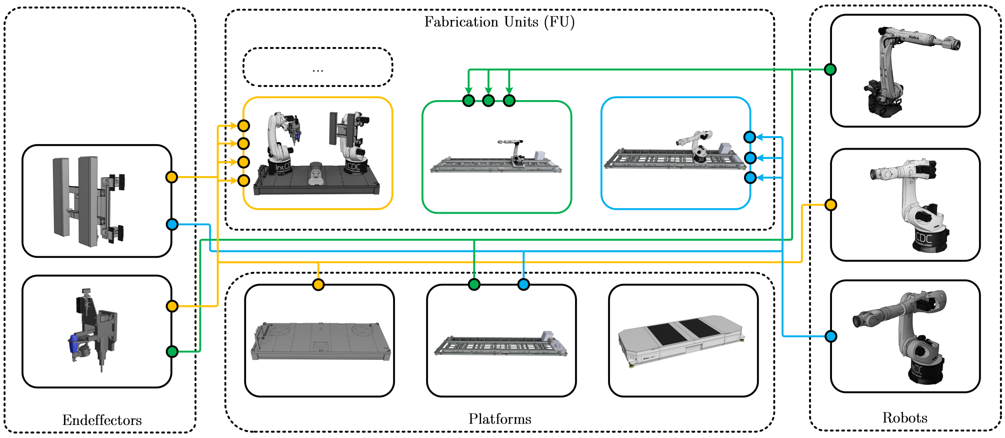


Figure 2. Composition of Modular Fabrication Units

This is necessary, for example, so that collisions of the module container with the ground are not permanently reported. A start file is created as an entry point for the launch of the digital twin. After the successful generation of the digital twin, this file is reported to the simulation manager.

3.6 Simulation

The automated simulation is managed according to figure 3 following model generation by the Model Composer. The Simulation Manager component is responsible for this. It receives pairs of digital twins and task descriptions to be simulated. The individual pairs are simulated according to their order. For this purpose, the digital twin together with the task description is automatically loaded into the simulation environment and started. During the simulation, monitoring data such as the movements of the robots or any collisions that occur are recorded. When the simulation is finished, the digital twin is stopped. The successful execution of individual tasks is reported by the task controllers of the FUs. If a task could not be executed successfully due to a collision or other errors such as reachability problems or too large tracking errors during path execution, the task is marked as failed. Using the monitoring data, errors such as collisions can be analyzed in detail and the component or system can be adjusted accordingly. If a task fails, the pair of the task description and system layout is marked as non-functioning.

Figure 4 shows the state flow of the Simulation Manager during automatic simulation. First, the digital twin is generated for a given layout (state 1). Then, the digital twin is started. After the successful model ramp-up phase (state 2) the simulation can be started (state 3). After the simulation is finished, the digital twin is stopped during the model ramp-down phase (state 4). In state 5, the generated data is deleted and the workspace of the model generator and the simulation manager is cleaned up. In this step, the results of the simulation are saved.

4 Implementation

The above method was implemented as a proof of concept and is in an early stage of implementation. The implementation is based on the open-source robotics framework Robot Operating System (ROS) using C++ and Python. Gazebo is used as the simulation system. The individual fabrication units (FU) and their subcomponents are based on the IntCDC fabrication module library containing different containers and robots. The Unified Robot Description Format (URDF) is used as description the model for robot kinematics with the XACRO tool from ROS. For motion planning, the MoveIt path planning library is used. In the current state, digital twins can be generated model-based and started or stopped automatically. During generation, all FUs are configured with the required components. All configuration and launch files are generated. In the simulation, the robots can follow the paths described in the tasks. Any collisions that occur are detected. Based on the simulation data, the system configuration or the fabrication tasks can be adapted accordingly. The actual manufacturing simulation with handling and assembly processes or subtractive and additive processing is currently not integrated and will be realized in the next steps.

5 Validation

The validation of the described concept is realized using different system layouts of the fabrication system for testing. For this purpose, 4 different system layouts are used as use cases with a sequence of motion tasks. The individual tasks describe movements that have to be executed by the robots. Use Case 1 consists of 5 fabrication

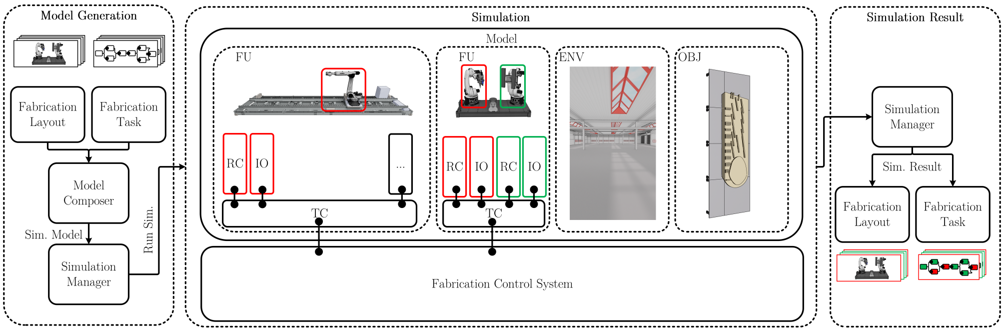


Figure 3. Simulation Workflow

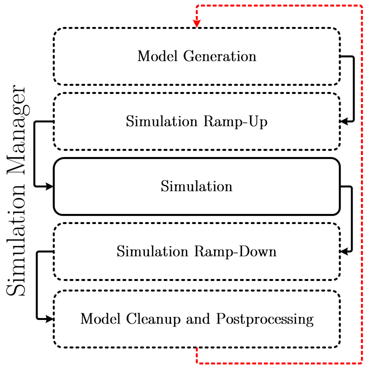


Figure 4. State Flow of the Simulation Manager

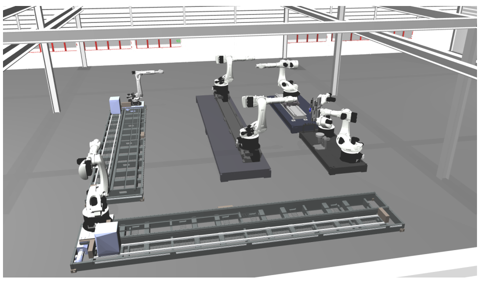


Figure 5. Use Case 1

modules with a total of 8 robots. The other use cases comprise 2 and 3 modules respectively. Use Case 4 is defined in such a way that collisions with the environment occur during certain tasks. The 3D model of the Large Robotic Construction Lab (LCRL) of the University of Stuttgart is used as a simulation environment.

The digital twin of use cases 1 and 4 can be seen in figures 5 and 6. The system layouts are defined in the configuration of the model generator. The generator iterates over the individual layouts. It generates the digital twin of the system according to the layout. The Digital Twin is then started and initialized. After the model is completely loaded, the simulation of the tasks is started and performed. After completion of the task simulation,

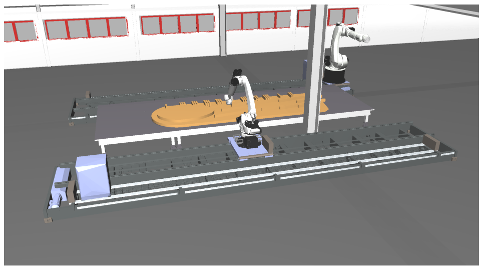


Figure 6. Use Case 4

the digital twin is deinitialized and stopped. The log data of the simulations are shown in Figure 6.

The log data shows the chronological sequence of the generation of the models. The models are first created (1). Then they are started (2) and the simulation is carried out (3). After the simulation is finished, the model is stopped (4) and the model generator is cleaned up (5). It can be seen that in simulation 4, as expected, collisions with the environment are detected. The validation shows that the implementation allows the automatic generation and simulation of digital twins for the described system. The automatic generation and simulation of a list of layouts are possible. The validation based on the current implementation shows that the presented approach works and that it provides a solution for the model generation and simulation for the described reconfigurable manufacturing platform for timber prefabrication.

6 Conclusion

This paper discusses the automatic generation and simulation of digital twins of a reconfigurable, robot-based fabrication platform for prefabrication in timber construction. The proposed method allows an easy and automated generation of these models. It allows the automated simulation of fabrication tasks described in a task graph for a given system layout. The primary objective of this approach is to enable co-design through integrated fabrication planning and fabricability analysis. Hereby it is

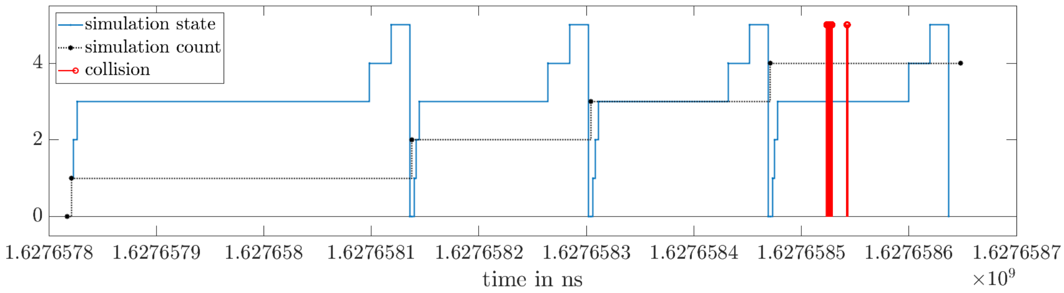


Figure 7. Simulation Log Data

possible to iterate quickly over different solutions. This permits efficient planning and validation of the fabrication and thus helps to keep downtimes for system reconfiguration between projects to a minimum. The next step is to extend the method to include an optimization procedure for the planning of a suitable system layout. In addition, the digital twin is to be extended to include a detailed simulation of manufacturing tasks such as handling, assembly, and subtractive and additive processes.

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References

[1] Annette Hafner and Sabrina Schäfer. Environmental aspects of material efficiency versus carbon storage in timber buildings. *European Journal of Wood and Wood Products*, 76(3):1045–1059, 2018. ISSN 0018-3768. doi:10.1007/s00107-017-1273-9.

[2] Annette Hafner, Stephan Ott, and Stefan Winter. Recycling and end-of-life scenarios for timber structures. In *Materials and Joints in Timber Structures*, pages 89–98. 2014. doi:10.1007/978-94-007-7811-5_8.

[3] Arno Behrens, Stefan Giljum, Jan Kovanda, and Samuel Niza. The material basis of the global economy. *Ecological Economics*, 64(2):444–453, 2007. ISSN 09218009. doi:10.1016/j.ecolecon.2007.02.034.

[4] Kristopher Orlowski. Assessment of manufacturing processes for automated timber-based panelised prefabrication. *Buildings*, 9(5):125, 2019. doi:10.3390/buildings9050125.

[5] Filipe Barbosa. Reinventing construction through a productivity revolution, 2017. URL `https://www.mckinsey.com/`.

[6] Hans Jakob Wagner, Martin Alvarez, Abel Groenewolt, and Achim Menges. Towards digital automation flexibility in large-scale timber construction: integrative robotic prefabrication and codesign of the buga wood pavilion. *Construction Robotics*, 4(3-4):187–204, 2020. ISSN 2509-811X. doi:10.1007/s41693-020-00038-5.

[7] J. Meiling. *Continuous improvement and experience feedback in off-site construction : timber-framed module prefabrication*. Luleå, 2010. ISBN 978-91-7439-180-0.

[8] Hans Jakob Wagner, Martin Alvarez, Ondrej Kyjanek, Zied Bhiri, Matthias Buck, and Achim Menges. Flexible and transportable robotic timber construction platform – tim. *Automation in Construction*, 120:103400, 2020. ISSN 09265805. doi:10.1016/j.autcon.2020.103400.

[9] Chai, Hua and Zhang, Liming and Yuan, Philip F. Advanced timber construction platform multi-robot system for timber structure design and prefabrication. pages 129–144. Springer Singapore, Singapore, 2020. ISBN 978-981-15-6568-7. doi:10.1007/978-981-15-6568-7_9.

[10] Martin Bechthold. The return of the future: A second go at robotic construction. *Architectural Design*, 80(4):116–121, 2010. ISSN 00038504. doi:10.1002/ad.1115.

[11] Jan Willmann, editor. *Robotic fabrication in architecture, art and design 2018*. Springer, Cham, Switzerland, 2019. ISBN 978-3-319-92293-5.

[12] Aleksandra Anna Apolinarska, Michael Knauss, Fabio Gramazio, and Matthias Kohler. The sequential roof. pages 45–59. Routledge, New York : Routledge, 2016., 2016. ISBN 9781315678825. doi:10.4324/9781315678825-4.

[13] Jan Knippers, Cordula Kropp, Achim Menges, Oliver Sawodny, and Daniel Weiskopf. Integrative computational design and construction: Rethinking architecture digitally. *Civil Engineering Design*, 2021. ISSN 2625-073X.

doi:10.1002/cend.202100027.

[14] Edward Glaessgen and David Stargel. The digital twin paradigm for future nasa and u.s. air force vehicles. In *53rd AIAA/ASME/ASCE/AHS/ASC Structures*, Reston, Virigina, 2012. American Institute of Aeronautics and Astronautics. ISBN 978-1-60086-937-2. doi:10.2514/6.2012-1818.

[15] Florian Jaensch, Akos Csiszar, Christian Scheifele, and Alexander Verl. Digital twins of manufacturing systems as a base for machine learning. In *2018 25th International Conference on Mechatronics and Machine Vision in Practice (M2VIP)*, pages 1–6. IEEE, 2018. ISBN 978-1-5386-7544-1. doi:10.1109/M2VIP.2018.8600844.

[16] Christian Scheifele, Alexander Verl, and Oliver Riedel. Real-time co-simulation for the virtual commissioning of production systems. *Procedia CIRP*, 79:397–402, 2019. ISSN 22128271. doi:10.1016/j.procir.2019.02.104.

[17] Thomas H.-J. Uhlemann, Christian Lehmann, and Rolf Steinhilper. The digital twin: Realizing the cyber-physical production system for industry 4.0. *Procedia CIRP*, 61:335–340, 2017. ISSN 22128271. doi:10.1016/j.procir.2016.11.152.

[18] Minos-Stensrud Mathias, Haakstad Ole Henrik, Sakseid Olav, Westby Baard, and Alcocer Alex. Towards automated 3d reconstruction in sme factories and digital twin model generation. In *ICCAS 2018*, pages 1777–1781, 2018.

[19] Jörg Christian Kirchhof, Judith Michael, Bernhard Rumpe, Simon Varga, and Andreas Wortmann. Model-driven digital twin construction. In *Proceedings of the 23rd ACM/IEEE International Conference on Model Driven Engineering Languages and Systems*, pages 90–101, New York, NY, USA, 2020. ACM. ISBN 9781450370196. doi:10.1145/3365438.3410941.

[20] Giovanni Lugaresi and Andrea Matta. Automated manufacturing system discovery and digital twin generation. *Journal of Manufacturing Systems*, 59:51–66, 2021. ISSN 02786125. doi:10.1016/j.jmsy.2021.01.005.

[21] Gerardo Santillan Martinez, Seppo Sierla, Tommi Karhela, and Valeriy Vyatkin. Automatic generation of a simulation-based digital twin of an industrial process plant. pages 3084–3089. IEEE, 2018. doi:10.1109/IECON.2018.8591464.

[22] Behrang Ashtari Talkhestani, Dominik Braun, Wolfgang Schloegl, and Michael Weyrich. Qualitative and quantitative evaluation of reconfiguring an automation system using digital twin. *Procedia CIRP*, 93: 268–273, 2020. ISSN 22128271. doi:10.1016/j.procir.2020.03.014.

[23] Hichem Haddou Benderbal, Abdelkrim R. Yelles-Chaouche, and Alexandre Dolgui. A digital twin modular framework for reconfigurable manufacturing systems. volume 592 of *IFIP Advances in Information and Communication Technology*, pages 493–500. Springer International Publishing, 2020. ISBN 978-3-030-57996-8. doi:10.1007/978-3-030-57997-5_57.

[24] Sihan Huang, Guoxin Wang, and Yan Yan. Building blocks for digital twin of reconfigurable machine tools from design perspective. *International Journal of Production Research*, pages 1–15, 2020. ISSN 0020-7543. doi:10.1080/00207543.2020.1847340.

[25] Kezia Amanda Kurniadi, Sangil Lee, and Kwangyeol Ryu. Digital twin approach for solving reconfiguration planning problems in rms. volume 536, pages 327–334. Springer International Publishing, 2018. ISBN 978-3-319-99706-3. doi:10.1007/978-3-319-99707-0_41.

[26] Jiewu Leng, Qiang Liu, Shide Ye, Jianbo Jing, Yan Wang, Chaoyang Zhang, Ding Zhang, and Xin Chen. Digital twin-driven rapid reconfiguration of the automated manufacturing system via an open architecture model. *Robotics and Computer-Integrated Manufacturing*, 63:101895, 2020. ISSN 07365845. doi:10.1016/j.rcim.2019.101895.

[27] Chenyuan Zhang, Wenjun Xu, Jiayi Liu, Zhihao Liu, Zude Zhou, and Duc Truong Pham. Digital twin-enabled reconfigurable modeling for smart manufacturing systems. *International Journal of Computer Integrated Manufacturing*, pages 1–25, 2019. ISSN 0951-192X. doi:10.1080/0951192X.2019.1699256.

[28] De-Graft Joe Opoku, Srinath Perera, Robert Osei-Kyei, and Maria Rashidi. Digital twin application in the construction industry: A literature review. *Journal of Building Engineering*, 40:102726, 2021. ISSN 23527102. doi:10.1016/j.jobe.2021.102726.

[29] Siavash H. Khajavi, Naser Hossein Motlagh, Alireza Jaribion, Liss C. Werner, and Jan Holmstrom. Digital twin: Vision, benefits, boundaries, and creation for buildings. *IEEE Access*, 7:147406–147419, 2019. doi:10.1109/ACCESS.2019.2946515.

[30] Dongmin Lee, Sang Hyun Lee, Neda Masoud, M. S. Krishnan, and Victor C. Li. Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. *Automation in Construction*, 127:103688, 2021. ISSN 09265805. doi:10.1016/j.autcon.2021.103688.

[31] Ye Zhang, A. Meina, Xuhao Lin, Kun Zhang, and Zhen Xu. Digital twin in computational design and robotic construction of wooden architecture. *Advances in Civil Engineering*, 2021:1–14, 2021. ISSN 1687-8086. doi:10.1155/2021/8898997.