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Impact of additive manufacturing and parametric design on the structure and economic efficiency of construction supply chains

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Abstract: Additive manufacturing and parametric design are anticipated to unfold potentially a strong momentum on costs regarding labor and material savings, as well as elevating automation and productivity within the construction industry. However, research on linking these technologies for use in the construction industry and analyzing the impact on the supply chain structure is scarce. Information in view of challenges regarding technical feasibility and requirements is limited. This paper aims to analyze the technology induced structural change of a construction supply chain and its thereby inherent influence on value creation and economic efficiency. A systematic literature review and a case study were conducted for understanding the impacts of combining additive manufacturing and parametric design. The impact on the structure of the supply chain is product specific, depending on the technology used to design, manufacture and automate as well as material performance, regulatory and technical requirements. Process steps can be encapsulated in technical modules driven by the digital characteristics of the two technologies. There are positive effects on (re-)working time, material consumption, waste reduction, strengthened innovative capacity and shorter delivery times, resulting in labour and cost optimization.

Keywords: additive manufacturing, parametric design, construction supply chain, mass customization, cyber-physical production systems, configure-to-order, handrail, economic efficiency, automation.

1. INTRODUCTION

1.1 Motivation

Productivity in the construction industry has not increased in the last 30 years (Reinecke et al., 2023). A decreasing availability of skilled workers, higher requirements from standards and regulations, as well as new challenges in terms of CO2 and resource efficiency, are coming up against a complex supply chain with many stakeholders and individual, demand-oriented building construction. At the same time, the demand for sustainable buildings is increasing (Francis et al., 2023). The use of innovative technologies offers the potential to increase efficiency across the industry. Additive manufacturing processes combined with parametric design potentially result in technological advantages and productivity increases in the construction supply chain.

1.2 Additive Manufacturing

Additive manufacturing (AM) refers to a production process in which the component is created by applying material layer by layer (Campbell et al., 2023). AM machines can be digitally integrated into the cyber-physical systems of production companies via numerical control systems. Thanks to the freedom of geometry in component production, batch size 1 can be realized for individual demand-oriented components at constant production costs. Additive printing processes that are particularly suitable for large-format prints in the construction industry include binder jetting, fused granular fabrication, 3D concrete printing and directed energy deposition for materials such as polymers, mineral building materials or metals (Paolini, Kollmannsberger & Rank, 2019). The components are designed specifically for the respective AM process and take the material requirements into account. This design for additive manufacturing (DFAM) enables the components to integrate the advantages of AM via design specifications and fulfil technical, qualitative, and economic requirements (Tuvayanond & Prasittisopin, 2023).

1.3 Parametric Design

Parametric design (PD) is an approach to design geometries using computational algorithms (Tedeschi, 2014). In contrast to conventional computer aided design (CAD) systems, the technical drawings of the components can be customized variably by entering values such as dimensions. The minimum and maximum values are programmed as value ranges in the algorithms. The component algorithm can also include technical requirements from standards and regulations such as statics, fire protection requirements, information on component connections or installation situations. Customized components can thus be generated automatically with reduced planning time, complexity and susceptibility to errors (Coenders, 2021). This component data can be transferred to an algorithmically generated computer aided manufacturing (CAM) process, which automatically generates the processing parameters of the AM machine and print paths. At the same time, upstream and downstream processes within the supply chain can be connected via application programming interfaces (API) for data exchange. The structure of the supply

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chain can thus be modified to increase productivity (see sec. 1.4, 3.2).

1.4 Construction Supply Chain

A typical supply chain in the construction industry consists of a complex network of participants who contribute various resources and technologies to the process from requirements analysis to dismantling (Yevu, Yu & Darko, 2021). Figure 1 provides an example.

Traditional Construction Supply Chain

1	Requirements analysis	(C)	11	Material procurement	(T)
2	Planning	(A)	12	Production, postprocessing	(M)
3	Design	(A,C,So)	13	Logistic	(L)
4	Bill of quantities	(A)	14	Assembly	(T)
5	Offer/tender	(A,T)	15	Acceptance	(Si,A,C)
6	Order/selection, award	(C,A)	16	Maintenance	(T)
7	Measurement	(C)	17	Dismantling, recyling	(C)
8	Execution plans	(A,T,So)			
9	Technical verfications	(Sp)			
10	Approval	(A,T)			

Parties involved
A Architect C Client L Logistician
M Manufacturer R Recycling company
Si Site Manager So Software supplier
Sp Specialist planner T Trades

Figure 1. Traditional construction supply chain, following Yevu, Yu & Darko (2021)

A traditional construction industry supply chain is long, slow and cost-intensive and does not exploit the current state of digital planning technology or efficient digital fabrication technologies (Reinecke et al., 2023; Thunberg, Rudberg & Karrbom, 2017; Xu et al., 2022). As Feldmann & Pumpe (2016) have shown, AM can generate a positive Economic Value Added (EVA) through a variety of value drivers within the supply chain. The use of standardization, concepts of product modularity and platform concepts have a favorable cost effect.

1.5 Objectives and course of the study

The objectives of this research are twofold. First, this study will identify the advantages and limitations of using AM and PD for building construction to understand how the technology can be utilized. Second, there is a need to validate the impact of AM on the economic efficiency of construction supply chains.

This study aims to demonstrate the potential of how the supply chain in the field of planning automation and AM can realize efficiency gains by highlighting various aspects through a systematic literature review according to vom Brocke et al. (2009) and a case study on a realized project. The project originates from the unikat.railings research and transfer project at Münster University of Applied Sciences. Unikat.railings automates planning and AM production on a platform and networks the parties involved in the construction process to efficiently realize large-format additive components such as railings for individual installation situations. The project analyzed in this study relates to the production of a handrail with the complex geometry of a spiral staircase. It illustrates the challenges and advantages of combining the technologies of PD and AM. This paper proceeds as follows: In Section 2 a systematic literature review is conducted to identify relevant research gaps. Section 3 provides an outline of the research methods applied. These encompass an extensive literature review and a case study. Findings on the challenges and advantages, as well as an digitally automated construction supply-chain-model are demonstrated in Section 4. After discussing the limitations of this study (sec. 5), the paper concludes with a summary of the findings and an outlook for future research.

2. STATE-OF-THE-RESEARCH

A systematic literature review was conducted to investigate the state of the research, following the approach by vom Brocke et al. (2009). Three main areas of research emerge from the practice-oriented contributions. These focus on initiating technological improvements and innovations in printing and materials technology, design and engineering software, and IT-enabled production and communication platforms. Publications in the area of printing and materials technology focus on research into new printing processes that can be reliably used with special materials in the printing process that meet technical and quality requirements (Xu et al., 2022).

Literature focusing on design and construction software, linking and data exchange with the Industry Foundation Classes (IFC) format for the Building Information Model (BIM) in the construction industry is often analyzed (Davtalab, Kazemian & Khoshnevis, 2018). Generative and parametric design approaches are described for the automated form-finding of CAD models. The integration of parametric design into a platform for the construction industry with robotic additive manufacturing is explained by He et al. (2020).

Investigations delving into the subject from an explicit theoretical perspective provide a range of relevant technical and economic topics and frameworks namely the AM process, the design process, basic AM induced supply chain, platform for cloud manufacturing and BIM (Singh et al. 2021). By linking individual topics such as AM with CAM or BIM, design for AM with digital fabrication, the resulting benefits, value contributions and challenges are analyzed (Tuvayanond & Prasittisopin, 2023). The effects on costs and productivity are emphasized with regard to the economic impact (Xianfei et al. 2019). To summarize, comprehensive and coherent perspectives on applying PD for various highly regulated components in the construction industry are sparse. Moreover, using AM to manufacture these components adds to this. Furthermore, the influences of technical necessary details and material properties for components with individual geometries and installation situations are not sufficiently addressed. At the same time the feasibility in different printing processes, country-specific regulatory framework conditions as well as component-specific automatable production and assembly processes are not mapped in the literature. As a result, component-specific supply chains that undergo structural changes and changes in value creation as a result of employing both AM and PD represent a research gap. The research gap identified above leads to the following research questions:

RQ1: How can combining PD with AM processes change the value creation in the supply chain of the construction industry?

RQ2: Which factors influence the economic efficiency of utilizing PD for AM in the construction industry?

3. RESEARCH METHODOLOGY

3.1 Overview

Considering the explorative nature of the research questions, a case study and systematic literature review were embraced to achieve notable results. To provide an comprehensive understanding about the interconnections of the addressed technologies and economic impact, the result of the systematic literature research were presented in section 2. In the following, the requirements and the affected process are elaborated using the case study.

3.2 Case study

The case study concerns a project of the unikat.railings research and transfer project at Münster University of Applied Sciences. Its purpose was to program modular component systems and to develop a structured construction process from planning through production and assembly to further utilization at the end of the life cycle.

The automation of technical planning as well as data exchange and communication between the parties involved in planning should be as efficient as possible. The processes and data connections around the PD were linked to automated AM processes as displayed in Figure 2. The process from demand to acceptance can be reorganized accordingly: The architect requires a specific component for the new building to be constructed. Instead of creating a new technical drawing with adjustments to the installation situation, the architect uses a parametric component system.

The aim of the case study was to analyze the technically and economically relevant details based on the case: a handrail with a complex geometry. The knowledge thus gained is to be used for a favorable structural adjustment of the value chain and to address factors impacting the economic efficiency.

3.2.1 Design

Three types of handrails were additively manufactured for a construction project for a retail shop. The handrails extend over three floors, have different technical designs and connections to glass railings, metal railings or are attached to the wall with steel brackets. They have complex free-form geometries, as the railings and stairs are spiraled and individually adapted to the installation situation in the building like shown in Figure 2. Each handrail segment is unique in its geometry and was planned and manufactured individually. The material used was a fiber-reinforced high-tech plastic, which was covered with a peeled, dyed leather. The handrails have a modular design and consist of segments that are friction-locked together, using internal magnetic connectors and adjusted to prevent twisting using internal positioning pins. AM in combination with PD based planning generated economic advantages over traditional production using 5-axis CNC-milled wooden elements and classic CAD planning due to process automation based on algorithms and the additive manufacturing process.

3.2.2 Requirements and process

Components installed in buildings are subject to numerous standards and legal requirements that differ from country to country. The choice of material based on its properties is of great importance. Factors such as the normal service life, fire behavior or environmental influences such as temperature, UV radiation or humidity depend on the material. At the same time, the mechanical properties of the components themselves and component joints are not only dependent on the material, but are also largely defined by the manufacturing process and the manufacturing parameters. A suitable carbon-fiber-reinforced polymer was selected for the handrails and a series of prototypes were also created in order to obtain the desired production-related mechanical properties for the additively manufactured components and the connections, such as the line width of the outer wall, infill pattern, infill density, component orientation, layer height, printing speed or temperature.

In the following, the process is presented in order to subsequently derive a product process for an optimized supply chain, addressing the planning and manufacturing challenges in Figure 3. The steps that were necessary to produce the handrail in the desired quality are described below. The functionality of the connection and attachment to the railing construction, as well as the assembly and cooperation within the supply chain with all parties involved in the construction had to be guaranteed.

Based on the regulatory and usage-induced requirements of a handrail for a new retail store with high aesthetic requirements, a leather-covered hand-rail for a spiral staircase and railing geometry was defined in the requirements analysis (1). The initial technical planning (2) and the design (3) were carried out in classic CAD from which bill of quantities (4)

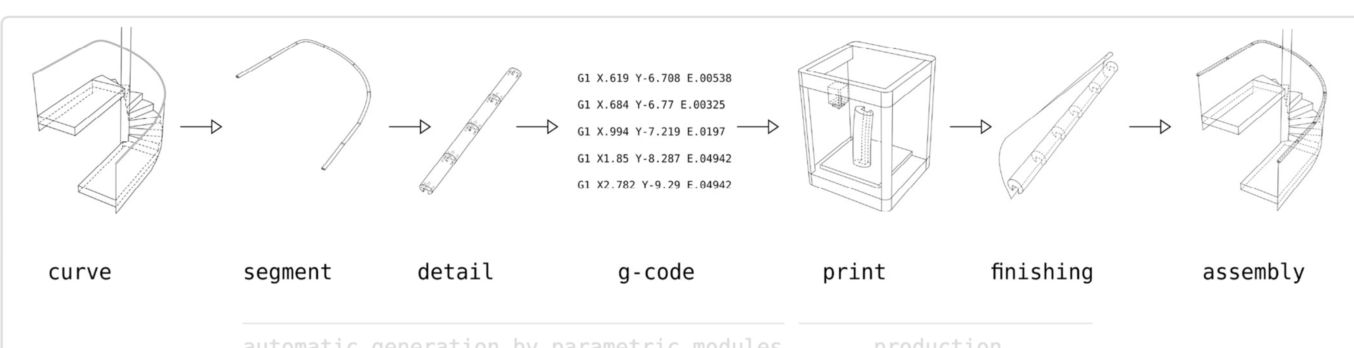

Figure 2. Parametric design handrail

were created. Before the quotation for the AM handrail can be generated in step (6), the additive feasibility (5) must be checked for plausibility. Corresponding to the requirements, material selection (5a) was followed by the slicing (5b) (CAM). Test prints (5c) include various processing parameters and component structure variants to evaluate the printing time for calculating the machine hours while achieving the required mechanical properties. The costs for the planning automation (5d) of the PD were analyzed. The joints were tested (5e) in terms of surface area and gap tolerances.

Figure 3. Project Construction Supply Chain

Due to the geometric complexity, planning automation of the design plans and manufacturing flexibility, the offer (6) was competitive in terms of costs with the AM and planning automation technologies used in comparison to the CNC milling. The order is then placed (7). The PD (8) was programmed to generate the design files. This software code generates the modular segments of the handrails by inputting a curve based on plan CAD data and exports them as a CAD file in STEP format (9). These modular segments contain the technical information for the component geometries, labelling, connections, subdivisions and alignments. A transfer interface was programmed to the final specification of the print profiles (10) for defining the slicing and material processing parameters. It imports the STEP files for automated print profile-specific G-code file creation (11) for the numerical control of the AM machines. Component production of the 3D print (13) starts with the input of the G-code files and the print material (12). The printed segments were post-processed and joined together to form one meter long elements. Delivery (14) was made to the service provider that carries out the assembly. After installing the staircase and railing, they carried out the initial assembly (15). This identified potential tolerance deviations (16) between the target CAD plan, the actual design of the preliminary work and the actual design of the handrail produced. The deviations in the preliminary work, which are often unavoidable due to the AM production process, can be compensated for by printing (17) a new, adapted module segment. For this purpose, the new data is used to run through steps (9)-(15) again. The newly printed segment ensures that the actual dimensions of the handrail and railing or wall fit exactly. The handrail is then broken down again into the one metre long elements (18) so that they can be delivered back (19) to the manufacturer for finishing (20) with leather or a veneer. The elements are then delivered (21) to the trade and the installation site for final assembly (22). This is followed by acceptance, maintenance and recycling (23-25).

4. RESULTS

In accordance with the discourse in sec. 2, the findings derived from the literature analysis do not yield robust insights into the specific inquiries under investigation. Consequently, the case study emerges as the principal mechanism for deriving consequential outcomes. In the case study, diverse **challenges** were observed during the initial implementation of the project process. In the planning automation of the CAD files, the free-form curve is the basis for generating the component geometries of the handrails. If this curve contains errors, for example due to the export or an inadequate data basis, the referencing of the curve in relation to the component geometry cannot be realized automatically using software codes. The curve must then first be adjusted manually.

The correct three-dimensional orientation for the non-planar subdivision of the handrail must be checked for complex, highly curved geometry sections. The same applies to the automated positioning of the offsets of the openings for the connection areas and the labelling of the segments. Only very small tolerance deviations are acceptable for the dimensions of the openings for the internal positioning pins and the magnetic connectors so that non-rotating force-fit connections can be created. A series of tests were required to generate these tolerances so that the interaction of CAD, CAM, material and printer hardware produces the required results.

The components were printed with support blockers in the areas of the openings. Due to the individual component geometries from the CAD, these blockers must adapt dynamically in the CAM. Automated parametric dimensional changes when entering the new values in certain segment areas are advantageous for the subsequent production of individual segments. For pre-assembly, additional openings already provided in the component on the long side for fastening to the railing are helpful. The anisotropic component behavior then has no effect on the component stability if an opening is subsequently added manually due to the continued constant adhesion between the individual layers. Infill reinforcement of these openings can additionally strengthen these areas. The challenges observed during process execution can be solved technically and encapsulated in the automation by programming the software code accordingly.

There are specific **advantages** to combining PD and AM technologies. These can be derived from the project process described and determine various factors of economic efficiency. Firstly, time required to create the CAD files for the technical planning of the handrail components is practically zero, as an individual technical drawing is not created for each component, but is instead automated by the software code. Secondly, the time for creating the machine-readable programming code called G-code is reduced by the automated CAM process. Thirdly, automation using software code reduces the susceptibility to errors.

Fourthly, due to the modularity of the handrail system, it is possible to remake individual segments with suitable dimensions in the event of tolerance deviations instead of having to replace complete elements. This reduces the working time for file creation, the machine hours, the amount of material used for reworking and the amount of waste from the segment to be replaced. At the same time, the duration and flexibility of necessary adjustments due to deviations is reduced, which is relevant in complex construction projects with many participants, coordinated project and time schedules, as well as completion deadlines. This can be a decisive advantage, potentially having a monetary impact due to contractual obligations regarding agreed completion dates and resulting penalties.

Fifthly, the material costs are reduced due to the AM process. The additive construction of the component means that only the material required to create the component geometry is used, whereas an alternative subtractive manufacturing process such as milling produces a lot of raw material as waste during production. The AM related freedom of geometry makes it possible to further reduce the amount of material required by realizing complex infill structures. The technology-induced advantages have the following direction of impact with regard to the factors of economic efficiency which are addressed in research question 2 (RQ 2): The reduced labour input lowers the cost factor in the calculation of manufacturing costs. The lower material consumption during production and the reduction in waste also have a positive effect on costs. The reduction in the number of machine hours needed, as well as the reduction in errors, decreases the costs and at the same time improves the competitiveness by reducing delivery times in complex construction projects, improving product quality and lowers the environmental impact. Increased use of the latest PD and AM technologies makes the company more attractive to skilled labour, which in turn may have a positive effect on productivity and innovative capacity.

With regard to research question 1 (RQ1), the case study provides insights on changes with regards to the structure of value creation. Influencing factors are:

a) **product technology variability.** Technical component requirements, regulations, material performance and the parameterization of planning and machine control determine the automation potential of the processes and thus the structure of the supply chain. A handrail made from a thermoplastic has a different value creation structure than a concrete shell wall. When using AM and PD, the supply chain is dependent on the specific product.

b) **the degree of technology integration.** Individual process steps can be combined and encapsulated in PD modules using software code. These parametrically encapsulated modules can contain information on component design, technical and regulatory component requirements, installation situation, machine processing and material parameters, and process them in relation to each other. Depending on which information on which technologies is integrated and to what extent, this changes the length of the supply chain. The supply chain described in Section 1.3 can be developed from a project into a production process by transferring several process steps into parametrically encapsulated modules. The supply chain has thus changed as shown in Figure 4. The findings of the case study correspond with the findings of the literature.

Digitally Automated Construction Supply Chain

1	Requirements analysis	(C)	7	Material procurement	(Pr)
2	Selection of plan dimensions and design	(A,C)	8	3D printing, postprocessing, joining	(Pr)
3	Automatic generation by parametric modules planning, design, bill of quantities, additive feasibility, offer/tender	(Pa)	9	Logistic	(L)
			10	Assembly	(T)
4	Order/selection, award	(C,A)	11	Acceptance	(Si,A,C)
5	Curve-Input after measurement	(T,Pa)	12	Maintenance	(T)
6	Automatic generation by parametric modules of g-code files containing: executio plans, technical verifications profile parametrerisation, approval	(Pa)	13	Dismantling, recyling	(C)

Figure 4. Digitally automated construction supply chain

The factors addressed in research question 2 (RQ2) with regard to economic efficiency relate to costs, competitiveness, productivity and innovative capacity. As derived above, these result from the advantages arising from the use of the combination of AM and PD.

5. LIMITATIONS

The study has several limitations. Both research methods employed are based on human judgement: in the systematic literature review to determine the significance of the literature included; in the case study for developing technical and procedural solutions. The resulting subjective bias reduces the validity of the findings due to a specific construction component, the results may differ from other components and applications. Further investigation by experts and practical evaluation are essential. The findings within the case study were derived from selected organizational units of the companies involved in this construction project. Consequently, the conducted design and process is distinctive to this particular scenario, including the resulting inherent limitations in representativeness and specific requirements.

6. CONCLUSIONS AND FUTURE DIRECTIONS

The aim of this paper was to identify the benefits and limitations of combining AM and PD within the construction industry, to understand the utilization of both technologies and their implications for supply chain structure and economic efficiency. Therefore this research was guided by two research questions. Findings to answer RQ1 (How can combining PD with AM processes change the value creation in the supply chain of the construction industry?) were derived from a systematic literature review and a case study. Firstly, the supply chain redesign and value creation is specific with regard to the construction product, due to the variability of the technology used to design, manufacture and automate; considering material performance as well as regulatory and technical requirements. Secondly, process steps 3, 6, 8 in Figure 4 defining the value creation along the structure of the supply chain can be encapsulated in technical modules driven by the digital characteristics of AM and PD, which impacts the length of the supply chain. With regards to RQ2 (Which factors influence the economic efficiency of utilizing PD for AM in the construction industry?), the key findings are positive economic effects on working and reworking time, error costs, material consumption, waste reduction, strengthened innovative capacity and shorter delivery times, resulting in labour and cost optimization.

On the one hand, this paper provides a practical contribution by offering a systematic approach to the specific use of AM and PD technologies for a dedicated construction component as a proxy, including technical details, requirements, challenges and advantages. Practitioners can apply this to unlock the productivity benefits these technologies provide. On the other hand, the study´s contribution to research consists of analyzing the link between AM and PD in relation to the construction supply chain and the associated implications on economic efficiency.

Future research is needed for broader empirical validation to increase representativity. Viable reference points could include expert interviews and further case studies, for example for other building component categories or AM technologies. In addition, the efficiency benefits of modular encapsulation could be measured quantitatively. Another research gap relates to the area of how regulation, certification, and technical requirements across the industry can promote rather than prevent the use of AM, PD, specific materials and automated processes for different construction components and how this will affect the supply chain. The combination of AM and PD offers promising potential in terms of economic aspects and innovative results from future research.

REFERENCES

Campbell, I., and Other, D.H.K.W (2023). *Wholers Report 2023*, chapter 1 page 19. *ASTM International*, Washington, D.C.

Coenders, J.L. (2021). Next generation parametric design. *Journal of the International Association for Shell and Spatial Structures,* 62(2), 153-166.

Davtalab, O., Kazemian, A., Khoshnevis, B. (2018). Perspectives on a BIM-integrated software platform for robotic construction through Contour Crafting. *Automation in Construction,* 89, 13-23.

Feldmann, C., Pumpe, A. (2016). A holistic decision framework for 3D printing investments in global supply chains. *World Conference on Transport Research - WCTR 2016*, Shanghai.

Francis, T., Horsey, T., and Other, L.P.W (2023). *Emerging trends in real estate.* https://knowledge.uli.org/-/media/files/emerging-trends/2024/emerging-trends-in-real-estate-europe-2024.pdf?rev=9a760c9be5f0413a89e9351a0ac6389a&hash=61B21911E27C6788589F237AF18E6D4E

He, R., Li, M., Gan, V.J.L., Ma, J. (2020). BIM-enabled computerized design and digital fabrication of industrialized buildings: a case study. *Journal of Cleaner Production,* 278, 123505.

Paolini, A., Kollmannsberger, S., Rank, E. (2019). Additive manufacturing in construction: A review on processes, applications, and digital planning methods. *Additive Manufacturing,* 30, 100894.

Reineke, B., Schäfer, A., and Other, S.M. (2023). *Ausbaufähig, Wie die Baubranche ihre Potenziale entfalten kann.* https://www.ey.com/de_de/forms/download-forms/2023/04/ausbaufaehig-wie-die-baubranche-ihre-potenziale-entfalten-kann

Singh, R., Gehlot, A., Akram, S.V., Gupta, L.R., Jena, M.K., Prakash, C., Singh, S., Kumar, R. (2021). Cloud Manufacturing, Internet of Things-Assisted Manufacturing and 3D Printing Technology: Reliable Tools for Sustainable Construction. *Sustainability,* 13, 7327.

Tedeschi, A. (2014). *AAD Algorithms Aides Design*, chapter 0 page 22. Le Penseur, Brienza.

Thunberg, M., Rudberg, M., Karrbom G., T. (2017). Categorising on-site problems - A supply chain management perspective on construction projects. *Construction Innovation,* 17 (1), 90-111.

Tuvayanond, W., Prasittisopin, L. (2023). Design for Manufacture and Assembly of Digital Fabrication and Additive Manufacturing in Construction: A Review. *Buildings,* 13, 429.

vom Brocke, J., Simons, A., Niehaves, B., Riemer, K., Plattfaut, R., Cleven, A. (2009): Reconstructing the Giant: on the Importance of Rigour in Documenting the Literature Search Process. *European Conference on Information Systems,* 17, 2206-2217.

Xianfei Y., Hexu L., Yuan C., Mohamed A. (2019). Building information modelling for off-site construction: Review and future directions. *Automation in Construction,* 101, 72-91.

Xu, W., Huang S., Han, D., Zhang, Z., Gao, Y., Feng, P. (2022). Toward automated construction: The design-to-printing workflow for a robotic in-situ 3D printed house. *Case Studies in Construction Materials,* 17, 1442.

Yevu, S.K., Yu, A.T.W., Darko, A. (2021). Digitalization of construction supply chain and procurement in the built environment: Emerging technologies and opportunities for sustainable processes. *Journal of Cleaner Production,* 322, 129093.