Automatic Manufacturability Evaluation and Process Planning for Cross-Laminated Timber

by

Emanuel Martinez Villanueva

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Engineering Management

Department of Mechanical Engineering
University of Alberta

ABSTRACT

The construction industry has constantly been researching and looking for improvements, and off-site construction has been one of the leading areas due to its advantages in controlled stations. A common material in off-site construction has been Cross-Laminated Timber (CLT) due to its sustainability, and programs like BIM now include this option for the developers. However, there is a lack of manufacturability feedback in the BIM model, and domain experts must be involved to define the machining and process planning. Therefore, this research develops in the machining automation of Cross-Laminated Timber in a robotic cell and target-path planning. Frist, an analysis is implemented to understand the areas of opportunity for manufacturing for CLT. The analysis was scientometric, comparing two research fields, construction in CLT and Industry 4.0. This review found two gaps: a digital twin or machining station for CLT and the automation of its programing. Second, once the need for a digital twin or machining station was found, its development was implemented in a virtual station based in RobotStudio. This machining cell makes use of industrial robots with an additional external axis and a flexible clamping station. This station is validated virtually with a CLT panel as a case study where its programming is done manually. Finally, as the station is ready to accept the programming for the machining of CLT panels, a target-path planning algorithm was developed. This algorithm processes the entire case study CLT panel and automatically detects the primitive geometries with the need for machining. Depending on the geometry and dimension, the algorithm creates a sequence of targets and assigns the robot and tool required for its machining.

PREFACE

The thesis in this document is the original work of Emanuel Martinez Villanueva. Two journal papers and one conference paper associated with this thesis have been submitted or published and are listed below. The document is framed in the paper format following the paper-based thesis guideline.

Chapter 2. Emanuel Martinez Villanueva, Jennifer Alejandra Cardenas Castañeda, Rafiq Ahmad, "Cross-laminated timber manufacturing in the context of Construction 4.0" *Automation.* DOI: 10.3390/automation3030023

Emanuel Martinez Villanueva performed the literature review while Jennifer Alejandra provided the support in selected chapters.

Chapter 3. Emanuel Martinez Villanueva, Harshavardhan Mamledesai, Pablo Martinez, Peyman Poostchi, Rafiq Ahmad, "Design and simulation of an automated robotic machining cell for crosslaminated timber panels" *31st CIRP Design Conference 2021 (CIRP Design 2021).* Available at DOI: 10.1016/j.procir.2021.05.026

Emanuel Martinez Villanueva designed and programed the robotic station in RobotSutdio. Harshavardhan and Peyman assisted in the design review of the system, and Pablo supported in the writing and review of the manuscript.

Chapter 4. Emanuel Martinez Villanueva, Pablo Martinez, Rafiq Ahmad, "Automatic target-path planning generation for robotic CLT machining station" *Automation in Construction.* (Under review)

Emanuel Martinez Villanueva was responsible for developing the programing and method. Pablo was the main support in the writing and review of the programing.

ACKNOWLEDGEMENT

Firstly, I would like to thank all the people who have supported my journey in the culmination of this thesis. Aside from my effort, this work results from the constant guidance and motivation of colleagues, friends, and family.

I would like to take the opportunity to dedicate my sincere gratitude to my supervisor Dr. Rafiq Ahmad, associate professor Department of Mechanical Engineering - University of Alberta, for his constant support, feedback, and encouragement in my research journey. I must mention that his support was not limited to the academic journey, but in my personal developments as well, especially in the last years when I had difficult times. Thanks to Dr. Pablo Martinez, senior lecturer at Northumbria University, for his outstanding guidance and magnificent feedback on the research articles published. Additionally, I would like to thank my colleagues David Baca, Roberto Monroy, Jennifer Cardenas, Rabiya Abbasi, and the LIMDA team for the support and advice in the development of the articles, simulations, and thesis. Also, this project is successful with the assistance of the Laboratory of Intelligent Manufacturing, Design and Automation (LIMDA) and the Department of Mechanical Engineering.

Finally, I wish to thank my wife, Karla Grisel Luna Romero, who was with me through all my graduate studies and stood with me on the journey of moving abroad. She also supported us as a family and prevented plenty of wrong turns. Last but not least, I would like to express my deepest gratitude to my parents, Ruben Martinez Lopez and Patricia Villanueva Jacinto for their support and encouragement in my life, who will always be remembered in my heart.

Thank You

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LIST OF ABBREVIATIONS

CLT Cross-Laminated Timber

IBC International Building Code

IABSE International Association For Bridge And Structural Engineering

BIM Building Information Modeling

WCTE World Conference Timber Engineering

IOT Internet Of Things

PHC Prefabricated House Construction

GHG Greenhouse Gas Emissions

SIP Structural Insulated Panels

CNC Computer Numerically Controlled

MDF Medium-Density Fiberboard

TIM Timber Construction Platform

STCR-TMS Single-Task Construction Robots – Technology Management System

MTC Mass Timber Construction

GLT Glue-Laminated Timber

SCL Structural Composite Lumber

CAPP Computer Assisted Process Planning

CAD Computer-Aided Design

CAM Computer-Aided Manufacturing

HPL High-Pressure Laminates

STL Standard Triangle Language

TCP Tool Center Point

TPPA Target-Path Planning Algorithm

Chapter 1 Introduction

1.1 Background and Motivation

Mass timber is a wood-based solution for the construction industry in its pursuit of sustainability, and Cross-laminated timber (CLT) is one of the most common materials used within mass timber construction [1], [2]. The construction industry is responsible for using multiple global resources, 40% of the energy, 25% of water consumption, and close to 30% of the global greenhouse gas emissions (GHG) [3]. Thus, there is a need for this thriving awareness to develop renewable materials that reduce resource depletion and help with multiple environmental concerns. CLT is a wood product made with multiple layers where each of them glued crosswise of each other to form a single material. Timber, a cellulose-based material, is commonly used for this renewable alternative. The first appearance of CLT was in Europe in the 90s, and it had different names in its development, like “x-lam” or “cross-timber” [4], [5] . Since then, the industry has considered CLT one of the best sustainable materials, and it has been an exciting topic for researchers. One example of the current work is the study from Nordin et al., whose work was dedicated to manufacturing CLT panels with tropical hardwood for better commercialization [6]. Another instance is the intelligent methodology to optimize the CLT panels required in buildings, removing material that is not needed or reinforcing those with higher performance requirements [7]. Yet, there are still many developing areas for Cross-laminated timber, and this study explores these prospective opportunities.

On the other hand, Industry 4.0 is the transformation of manufacturing processes where multiple technologies are integrated within a production environment, characterized by its high virtual, digital, and technological performance [8]. This revolution has mainly taken place in the manufacturing sector; however, the construction industry is starting to take features from the new technology to improve performance and reduce cost [9]. The new paradigm that bounds these two fields is referred to as Construction 4.0, which focuses on digitalizing the construction processes [10]. One example of the progress is the work of Webster [11] , who uses Artificial Intelligence (AI) to route and harness wires and cable layouts in building construction [11]. On the other hand, we have the work of Kim et al., who made a vision-based hazard avoidance system with the help of augmented reality and informed the workers of potentially hazardous situations [12].

A solution the industry has taken is off-site construction as it can take advantage of pre-manufacturing full building entities in a controlled environment, and it can use green materials such as CLT. Off-site construction has taken advantage of software like BIM due to its integrated tools covering from design up to the bill of material; however, the manufacturability of the projects is a missing part in BIM [13]Click or tap here to enter text.. The integration of manufacturability tools in BIM is a research field that authors are starting to consider [14], [15]. For instance, Shi et al. made an algorithm to automatically detect the type of machine and the framing points required depending on the shape of a wood frame [16], [17]. Nevertheless, there is no tool at the current moment for detecting the manufacturability of cross-laminated timber within BIM. A great part of the problem in understanding the manufacturability of the construction is the exchange of data among components, making it even harder for Industry 4.0 to be implemented, a critical feature for cyber-physical systems [18].

While the integration of manufacturing tools is still in development in the construction industry, mechanical parts have greatly benefited from this topic, mainly named computer-aided process planning (CAPP). CAPP can be considered as the link between computer-aided design (CAD) and computer-aided manufacturing (CAM), where the principal duty of CAPP is to give detailed instructions to the manufacturing machines. CAPP has had multiple approaches in the last decades, but one of the most well-known techniques is feature-based analysis, which consists in the interpretations of the geometrical and topological features of the entities to process Click or tap here to enter text.. Once the shape of the part has been analyzed, manufacturing instructions are obtained from CAPP. Therefore, if there is already a technology for the automation of mechanical parts, it is possible to assume its implementation in construction-based products like cross-laminated timber. Thus, looking to push the industry into a Construction 4.0 field, this study intends to develop an automated system for manufacturing CLT panels.

1.2 Research objectives

The objective of this thesis is derived from studying the benefits of CLT in construction and the needs it has for Construction 4.0. The principal research objective of this thesis can be reduced to *"Develop an automated system for the manufacturing of Cross-Laminated Timber."*

For an easier understanding of the progress of this research, the **objectives (Os)** are subdivided into the following actions:

O1. Understand and detailed review of the research on Cross Laminated Timber in construction and compare the findings with Industry 4.0 advances to find key research areas and future trends of CLT through scientometric analysis.

O2. Design and develop a virtual station for machining cross-laminated timber with real-world data, and use any insight in the literature review.

O3. At the base of the machining robotic station, automate the path planning for the machining of CLT panels.

This study has achieved all the objectives presented above where the machining robotic station is based on the software RobotStudio®, and the algorithm developed for the automatic path planning is found in a python script. This algorithm can be included as an addon later on in commercial software like BIM.

1.3 Thesis Structure

The thesis outline is shown in a visual aid in Figure 1-1, where the entire document consists of five chapters. Chapter 1 introduces the research background and motivation for the field of manufacturing cross-laminated timber. Chapter 2 presents a scientometric literature review where two fields were compared, construction with CLT and Industry 4.0 for CLT. This chapter addresses the first research objective as the research gaps are found. Chapter 3 shows the development of a virtual machining station for cross-laminated timber with the use of industrial robots in RobotStudio®. Here the second research objective is achieved as the virtual station is validated to manufacture CLT panels. Chapter 4 presents the target-path planning algorithm required for the automation of the previous machining station. Here a deeper look into the geometric interpretation of each machining cavity is described, as well as the way of how the algorithm assigns each robot and tool. Finally, Chapter 5 is the conclusion of the thesis, including the research contributions, the limitations of this thesis, and possible future work for this research.

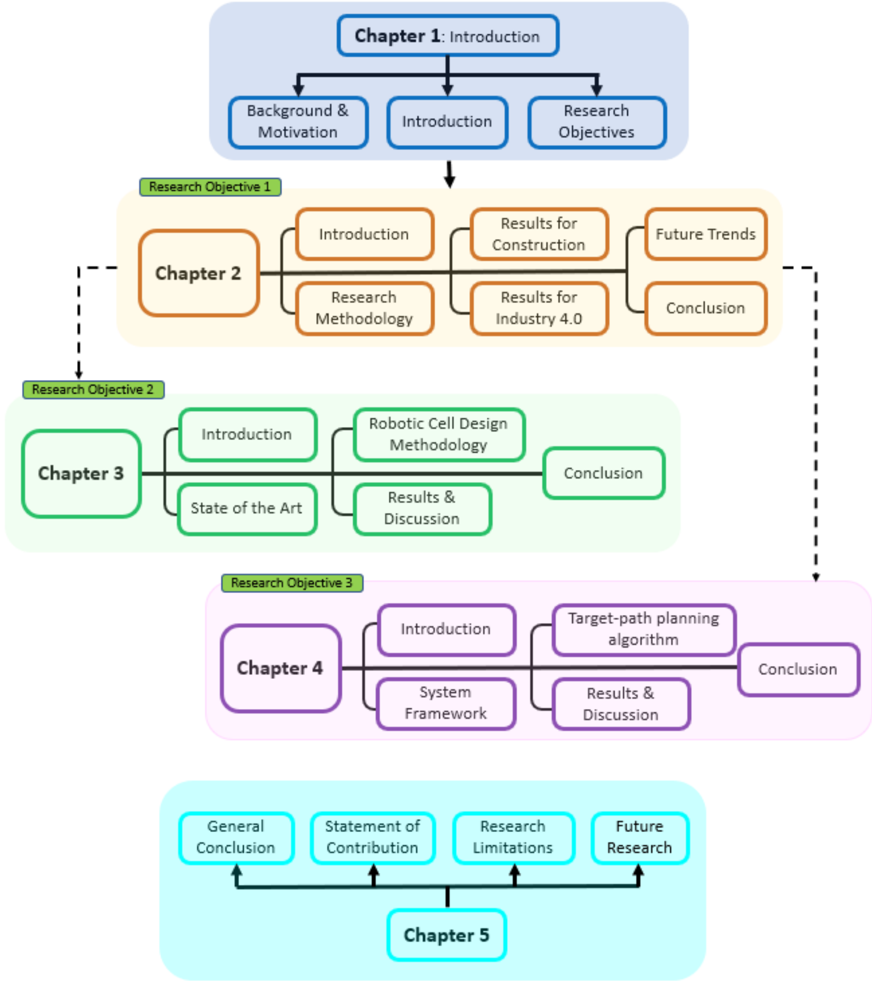


Figure 1-1. Visual aid representation of thesis layout.

Chapter 2. Literature Review on Manufacturing State for Cross-Laminated Timber

2.1. Introduction

The construction industry considers CLT as one of the best sustainable materials, and it has been a great topic for authors in the last years [19]. Yet, even though it is possible to find multiple journals about the material, the authors are interested in its manufacturability, especially looking from an Industry 4.0 perspective. Thus, this study will delve into the progress Industry 4.0 has made with Cross Laminated Timber (CLT), aiming to find possible areas of opportunity.

This chapter will highlight the important developments in this field using the "scientometrics approach," which is defined as those quantitative methods that deal with the analysis of science viewed as an information process [20] Click or tap here to enter text.. Scientometrics has already been used in other journals in construction-related reviews, like computer vision [21], or Building Information Modeling (BIM) [22]Click or tap here to enter text.. Nevertheless, the difference in this article is the comparison between two construction-related fields. This study intends to analyze the current state of both fields in construction, CLT, and Industry 4.0, so it is possible to identify the research gap from a manufacturing perspective. It is worth mentioning that this work cannot be done with the keyword "manufacturing" in the inquiries as this closes the results to less than 40 documents in Scopus. This limited result could lead to bias understanding of the research field, and the actual trends and gaps will be missed. Therefore, an independent review for each is attempted, and an examination of the intersection of both results is done to understand the opportunity and trends for manufacturing research.

2.2. Research Methodology

An array of multiple academic papers, journals, and conferences, were gathered to fulfill the objectives of this study. The Scopus database was used to obtain a collection of publications. Naturally, a limitation of research scope was set as the study cannot cover the entire universe of research articles [23], [24]. The key points for each academic entity will be defined by its title, keywords, abstract, and main contributions. This article's methodology is discussed below, and visual aid is found in Figure 2-1.

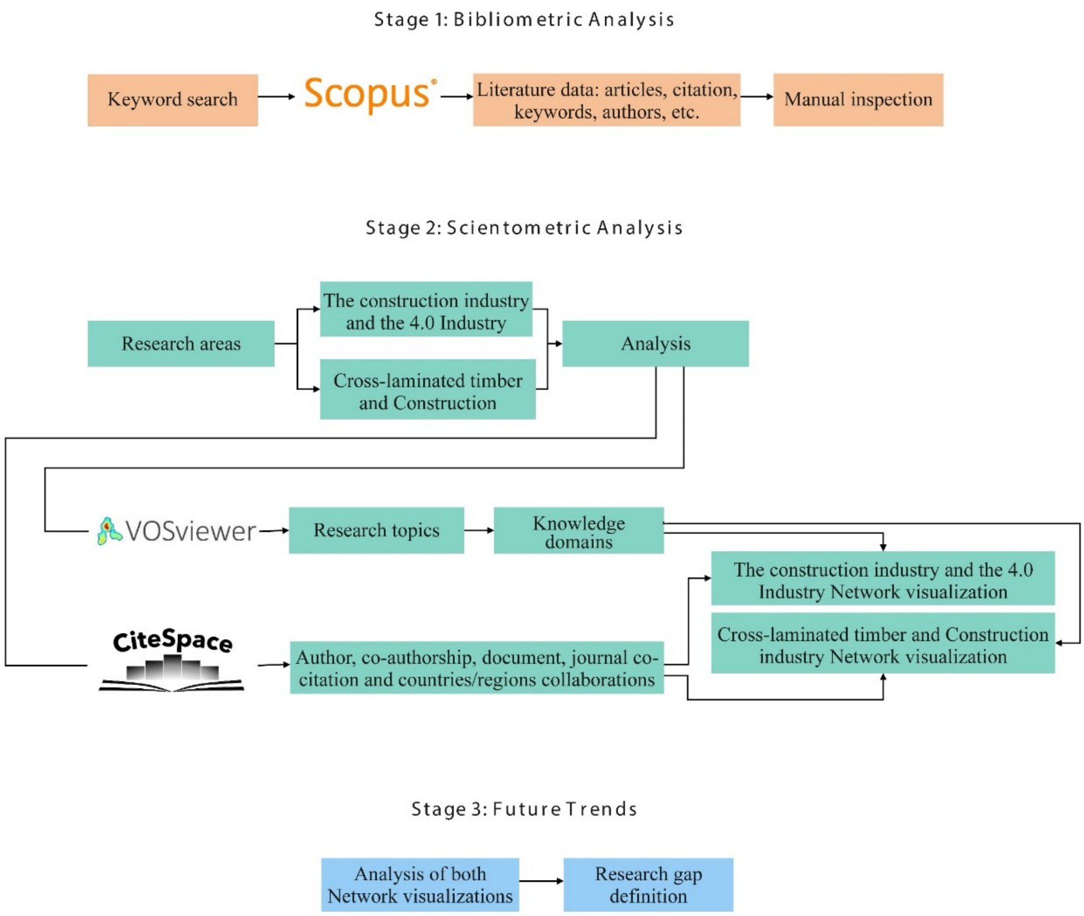


Figure 2-1. Overall view of the suggested research methodology.

2.2.1. Bibliometric Analysis

Any scientometric or bibliometric study will rely heavily on its data acquisition as this defines the academic articles from which any arguments will be derived.

Therefore, the database selection and screening strategy have to be done meticulously. The Scopus database was chosen in this study because its literature source has an extensive range of coverage on the construction-related research subject compared to other literature databases like PubMed, Google Scholar, Web of Science, and others [21], [25], [26]. Other academic databases cannot match Scopus for research in multidisciplinary fields, like the ones mentioned above, and it has the advantage of possessing an extensive list of international academic journals. The current publications of Cross-laminated timber (CLT) and Industry 4.0 connected to the construction industry in the database used for this analysis were recovered by using keywords, i.e. "cross-laminated timber*", "4.0 industry*" and "construction*" (the wild character * is implemented to acquire variations of the same word, like "cross-laminated timber" or "mass timber"). To fulfill the goal of this article and to narrow the results obtained, the keywords used were: ({Cross-laminated timber} OR {Cross-Laminated Timber} OR "Cross-laminated timber*") AND ("construction*"); and ({Industry 4.0* ") AND ("construction*"). Note that Scopus use curly brackets ({}) for a specific word search. The inquiries were made in two different sets because otherwise, the result would not pass 100 documents.

The keyword search in the literature database was implemented as "title/abstract/keyword", so all the entities with the keywords matching the criteria above in the title, abstract, or author-defined keyword section are retrieved. The inquiry was closed for the last 20 years, from March 2002 to April 2022; however, the results obtained show a first appearance since 2006 and an increasing trend in the research field, showing the importance and interest for CLT in the construction research field. Therefore, the inquiry for Industry 4.0 was limited to the same period for coherence. A scrutiny search on the array of publications was conducted to purify the results obtained and remove anything unrelated to the engineering scope. An example is a keyword "CLT" used in initial inquiries, yet, it was later released as it brought a vast number of publications in the subject area of mathematics as it had a different acronym interpretation in this field. The scope of this study was closed to exclusively entities from peer-review English journals or conference proceedings. An additional cleaning process was done on the remaining entities of the inquiry; in this step, the title and abstract were inspected manually to remove any paper from an irrelevant journal or conference proceeding. The academic data was used for the bibliometric analysis once the entire set was cleaned. For a more precise understanding, the initial results given by Scopus were over 2000 documents just for the CLT inquiry, but it was refined to 817 with the first change on search criteria; then, close to 753 with the manual screening, 403 of journal papers, and 350 of conference papers. The irrelevant journals removed were excluded thanks to the subject area or the different context of the acronym "CLT" in mathematics.

2.2.2. Scientometric Analysis

Scientometrics is considered a sub-field of infometrics, and it can be defined as a technique that measures and analyze scholarly literature [27] . Scientometric studies can be found since the 1970s in the literature, and it has been applied to multiple research subject areas, like Medicine, Physics, Astronomy, and others [28]–[30] . There are multiple research topics for Cross-Laminated Timber and 4.0 industry in construction. It will be complicated to get an overall representation of both fields with a traditional literature review. Even though manual reviews provide knowledgeable critical synopsis of any research field, it is limited to the number of journals one author could consider [31], [32] . Thus, this article suggests a comparative review of CLT and Industry 4.0 in construction-related publications with the aid of scientometric analysis to get a clear visualization and mapping of the research areas. The technique includes bibliometric tools for academic journals and conferences and is used to graph its framework and development on diverse topics, thanks to the big academic dataset. With the help of network modeling and graphs, the scientometric method targets to evaluate the big picture of the research knowledge and tries to provide questions that researchers may look further in later studies, along with techniques the scientists have used to fulfill their goals. Mapping the overall work on Cross-laminated timber and Industry 4.0 for construction will allow lecturers to understand the global mindset of academic patterns and tendencies in the fields. In academic content, it is considered that keywords and abstracts provide a well-defined and terse description of their work, where it is common to use keywords as pieces of analysis to detect highlighted groupings that may affect the structure of the researched field. This paper analyses the literature on CLT and Industry 4.0 in construction in terms of keywords and abstract terms to understand the researchers' options as much as possible. The next research techniques were enforced to obtain academic patterns: Keyword co-occurrence analysis and clustering, country co-occurrence and co-citation, co-author and burst detection, and abstract term cluster analysis. The study starts with keyword and author co-occurrence analysis which gives an accumulated representation of the entities and the nodes in the network map to supply evidence for the next clustering analysis. Next, the burst detection drops deeper insight into the relative adjustments over time to identify tendencies and differences in CLT and Industry 4.0, contrary to the prior analysis that only gave a static picture of the entire research field. In addition, abstract term clustering shows investigation patterns within the field with more scrutiny and highlights different research topics associated with outlining the conceptual research structure. These scientometric methods have been endorsed in former alike studies.

2.2.3. Future Trends

Future trends indicate the technologies or developments that will occur in the not-too-distant future, which allows us to understand and analyze what is required to get to that step forward [33] . Understanding trending topics in the current state of the academic field will allow readers to understand which subjects are highly relevant within these domains. The study started by delimiting the research into two subjects: The construction industry and Industry 4.0; the Cross-laminated timber and construction industry. It was decided to delve only into cross-laminated timber in construction for the purposes of this analysis. The cluster analysis of the construction industry and the 4.0 industry was delimited because it covers a large number of topics that are not relevant to the intention of this research; by going too profound, it will be difficult to obtain the main trending topics of this area. This paper used the networking visualizations obtained from CiteSpace and VOSviewer to analyze the clusters captured and a comparative review between them to understand the relationships between the different trending topics. The resolution of the trending topics of both research areas was used to examine the intersection between them and thus define the research gap.

2.3. Results for Cross-Laminated Timber in Construction

2.3.1. Data Acquisition

The first search strategy, keywords, as mentioned above in Section 2, is used to identify pertinent academic papers in journals and conferences; a summary of the most relevant results is shown in Table 2-1. Most of the articles lay in journals for structural engineering, covering both research fields CLT and construction, including

Engineering Structures, *Bautechnik*, and *Journal of Building Engineering*. The second type of journals found in the array is those for material properties, like *Construction and Building Materials*, *Wood and Fiber Science*, and *Applied Acoustics*. Additionally, there is a substantial appearance of journals for sustainability, like *Sustainability (Switzerland)*, *BioResources*, and *Building and Environment*.

Among all the sources, *World Conference on Timber Engineering* is the conference proceeding with the highest number of contributions, 168 publications which cover 48 percent of all the conferences, and it even surpasses the biggest academic journal, which has only 36 articles. Two other relevant proceedings are the *International Congress on Noise Control Engineering* and *IABSE (International Association for Bridge and Structural engineering),* providing 23 and 19 articles accordingly, both being on the top list of contributors for this field. Remarkably, a great part of the publications found held less than 4 articles related to this field: 40.45% of the academic journals and 24.29% of the conference proceedings were published in this condition.

Table 2-1. List of most broadly read academic journals and conference proceedings from January 2006 to March 2022 that had publications related to Cross-laminated timber in construction.

Journal title	**Number of articles**	**% Total Publications**
Engineering Structures	36	8.93%
Construction and Building Materials	33	8.19%
Journal of Structural Engineering (United States)	19	4.71%

Bautechnik	15	3.72%
Journal of Building Engineering	15	3.72%
Sustainability (Switzerland)	14	3.47%
BioResources	12	2.98%
Buildings	12	2.98%
Energy and Buildings	9	2.23%
Structures	9	2.23%
European Journal of Wood and Wood Products	8	1.99%
Wood and Fiber Science	8	1.99%
Journal of Structural and Construction Engineering	7	1.74%
Building and Environment	6	1.49%
Journal of Materials in Civil Engineering	6	1.49%
Journal of the Korean Wood Science and Technology	6	1.49%
AIJ Journal of Technology and Design	5	1.24%
Journal of Architectural Engineering	5	1.24%
Journal of Cleaner Production	5	1.24%
Structural Engineer	5	1.24%
Wood Material Science and Engineering	5	1.24%
Applied Acoustics	4	0.99%
Applied Sciences (Switzerland)	4	0.99%
Energies	4	0.99%

Conference title	**Number of articles**	**% Total Publications**

World Conference on Timber Engineering	168	48.00%
International Congress on Noise Control Engineering	23	6.57%
IABSE - International Association for Bridge and Structural Engineering	19	5.43%
International Conference on Structures and Architecture	12	3.43%
Annual Conference of the Canadian Society for Civil Engineering	10	2.86%
Nordic Symposium on Building Physics	8	2.29%
International Congress on Sound and Vibration	6	1.71%
Structures Congress	6	1.71%
International Conference of the Association for Computer-Aided Architectural Design Research in Asia	5	1.43%
International Congress on Acoustics	4	1.14%
International Conference on Structural Engineering, Mechanics and Computation	4	1.14%
International Conference and Exhibition on Fire and Materials	3	0.86%
Australasian Conference on the Mechanics of Structures and Materials	3	0.86%

A graph of the timeline with the number of publications per year is presented in Figure 2-2; this includes both academic journals and conference proceedings; and, as a note, the search was done looking for any articles from the last 20 years (starting on 2002), but the earliest article was found from 2006. This figure shows a clear upward trend of publications that started to rise in 2010, allowing us to say that Cross-laminated timber is of great interest to the construction industry. There are two-time slots that show a clear pike of publications; first, between 2015 and 2016, the number of articles almost tripled between one year and the other; second, between 2017 and 2018, the publications had a 117% increase since the previous year. Curiously, The International Building Code (IBC) started to recognize CLT products sin2015 for their use in primary structural elements (beams, columns, floors, etc.) [34], [35] . Additionally, it is important to mention that this graph shows a number of 17 publications for 2022; however, making an interpolation, we could estimate the number of 169 articles and conferences for the entire year.

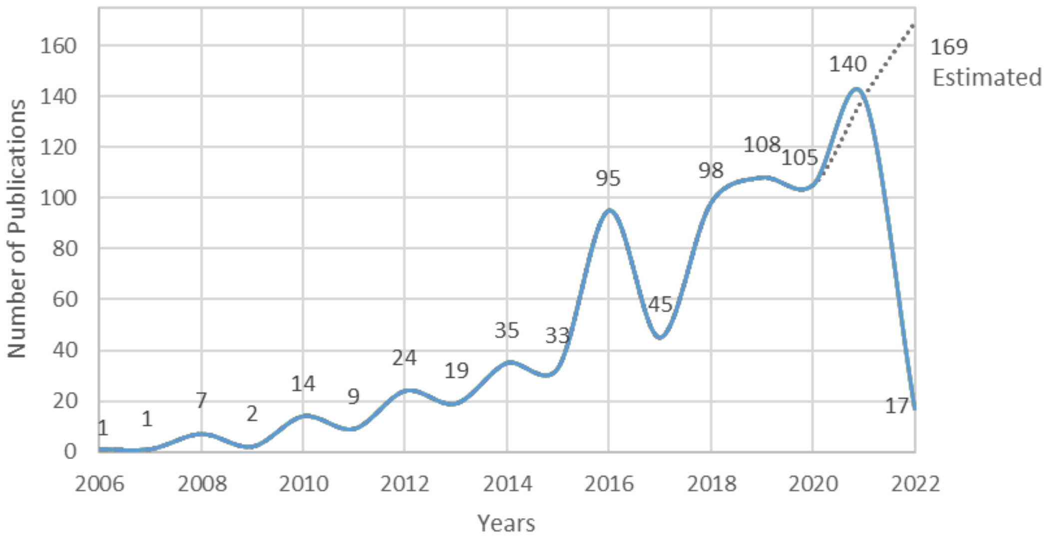


Figure 2-2. Historical trend of published studies in Cross-laminated timber (CLT) for construction (period 2006–2022).

2.3.2. Keyword Co-occurrence Analysis

Authors use keywords to represent the main content of the published articles and to display the scope areas researched within the limits of any domain [36]–[39] . In this study, the keyword co-occurrence analysis in the research area of Cross-laminated timber and construction was generated with the VOSviewer software. The bibliometric analysis results of the literature are displayed with a keyword's network. The map generated by VOSviewer is a distance-based network where the space between nodes represents the strength of the relation between two knowledge domains [38], [39] . A longer distance usually implies a weaker bond between the two nodes. The node or item label size is directly proportional to the sum of articles where the keyword was found. Different colors represent different groups of knowledge obtained with the clustering technique of VOSviewer [40], [41] . The threshold for the minimum number of occurrences was 20, so 73 of the 4,872 keywords meet these criteria for a node. The threshold of 20 was selected based on the multiple iterations with different parameters to obtain optimal clusters. The network map for the co-occurrence keywords is shown in Figure 2-3. This map has 73 nodes, 1885 links, and a total link strength of 9543. A summary of keyword data for the network map can be found in Table 2-2, where the average published year, the number of links, and strength are placed.

Table 2-2. List of selected keywords and relevant network data.

Keyword	**Occurrences**	**Average year published**	**Links**	**Total Link Strength**
Cross-laminated timber	546	2018	111	3698
Wooden buildings	172	2018	109	1428
Wooden construction	107	2018	103	918
Building materials	94	2017	103	786
Timber construction	94	2017	98	660
Walls (structural partitions)	90	2018	105	751
Floors	85	2017	102	682
Structural design	83	2018	102	686
Construction industry	82	2018	102	646

Architectural design	71	2018	97	619
Construction	68	2017	103	588
Buildings	66	2016	98	600
Stiffness	65	2019	93	533
Reinforced concrete	56	2018	86	441
Wood	54	2017	101	475
Seismology	50	2018	80	409
Seismic design	49	2018	81	457
Finite element method	48	2018	88	371
Shear walls	48	2018	73	391
Timber buildings	48	2018	85	408
Building codes	47	2017	95	415
Laminated composites	47	2018	101	425
Tall buildings	46	2017	101	445
Timber structures	46	2017	97	363
Wood products	46	2017	86	415
Sound insulation	45	2017	58	296
Sustainable development	45	2018	76	363
Lamination	40	2017	81	366
Office buildings	39	2017	84	318
Design	38	2016	92	341
Life cycle	38	2019	65	319
Housing	36	2018	68	301
Moisture	35	2019	52	209
Concretes	33	2017	87	289
Building construction	32	2018	78	252
Screws	32	2017	77	275
Residential building	31	2016	78	260
Engineered wood products	30	2017	76	291
Forests	30	2014	77	300
Gluing	30	2018	66	254
Bending tests	28	2019	55	200
Building	28	2019	77	215

Forestry	28	2017	65	202
Product design	28	2017	71	235
Fire resistance	27	2017	71	218
Architectural acoustics	26	2016	40	165
Fasteners	26	2016	67	224
Laminated veneer lumber	26	2018	75	224
Lumber	26	2018	72	228
Self-tapping screws	26	2018	67	212
Environmental impact	25	2019	55	199
Structural systems	25	2016	67	203
Connections	24	2016	66	225
Fires	24	2016	62	203
Mass timber	24	2019	58	165
Seismic response	24	2019	59	206
Testing	24	2017	67	198
Acoustic noise	23	2017	38	173
Acoustic variables control	23	2016	39	167
Structural analysis	23	2016	68	223
Bending strength	22	2019	43	145
Earthquakes	22	2017	64	205
Adhesives	21	2019	49	130
Damping	21	2018	59	162
Energy efficiency	21	2019	46	122
Global warming	21	2019	50	195
Loading	21	2019	63	190
Seismic performance	21	2018	52	156
Structural frames	21	2017	59	181
Structural performance	21	2017	67	182
Wall	21	2019	63	210
Energy dissipation	20	2018	51	157
Shear strength	20	2019	58	154

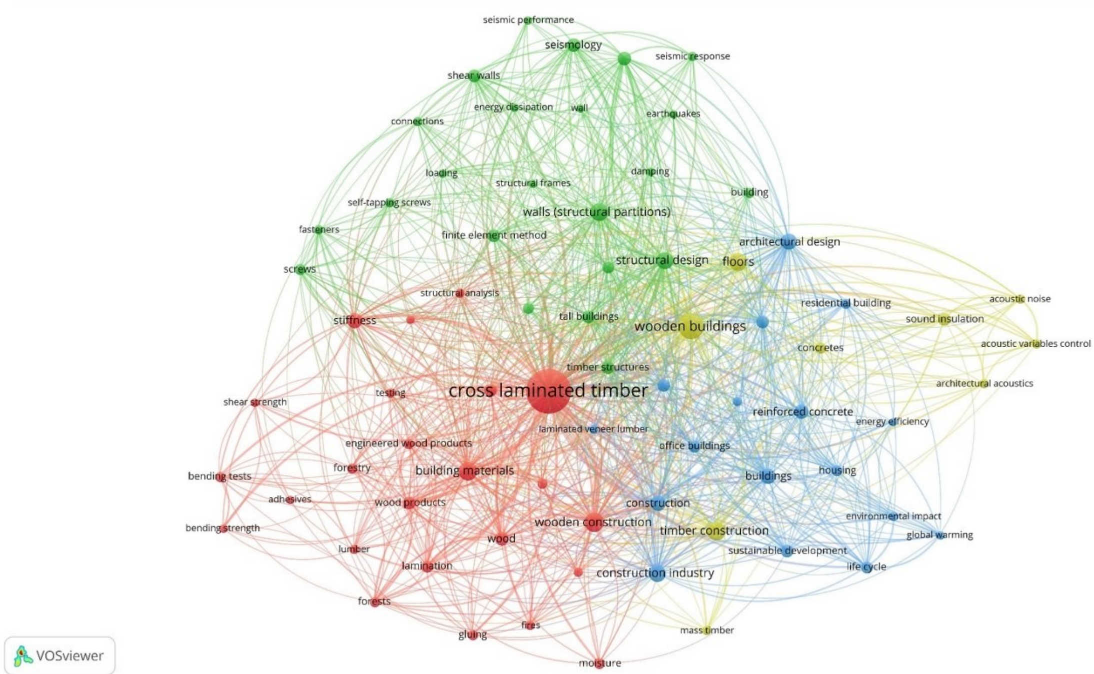


Figure 2-3. Network map of co-occurring keywords related to Cross-laminated timber in construction (2006–2022).

Each keyword has an occurrence number attached to it, as shown in Table 2-2, and this metric represents the times this search word was retrieved from the academic dataset in the author keywords. For instance, aside from the principal keyword "cross-laminated timber", the second keyword with 172 occurrences is "wooden buildings", meaning that researchers had spent extensive time looking into this field. Another important metric provided in Table 2-2 is the average year published, which represents the average time period where a certain keyword was used by authors in their articles. Notably, between the years 2014 and 2016, you could find 11 keywords, like "buildings", "design" and "residential building", indicating the initial interest of researchers in the use of CLT in construction. On the other hand, it is possible to find 15 keywords just in the year 2019, and the results show words such as "stiffness", "bending strength" and "moisture", showing the interest in academia to obtain the characteristics of CLT as construction material. Additionally, there are significant keywords showing up this year, like "life cycle", "environmental impact" and "global warming", highlighting the interest of researchers for a more sustainable material in this field. Now, the metric "links" represents the number of linkages between a specific node and others, and the total link strength indicates the total strength counted for a certain node [42] . For example, the total link strength of "structural design" is 686, positioning this keyword in the top list among all the keywords, showing in substantial relation between cross-laminated timber and structural design.

Network maps are usually a static representation of data that is not considering changes in a timeline, including keyword co-occurrence; however, VOSviewer is able to include a color code-based network overlaid in the same map of the keyword co-occurrence to show the transition of the nodes based in the average year of each keyword. Thus, Figure 2-4 represents the evolution of Cross-laminated timber in the construction industry over the last sixteen years. As a note, not all the keywords extracted from the literature are included in the network, as only those representative words with an occurrence of 20 are displayed. This constraint, curiously, reduced the span of time provided by VOSviewer and forced the map to start in the year 2016, just one year after the acceptance of CLT in the International Building Code. Looking at the map, it is possible to notice general words such as "buildings", "residential building", "fasteners" and "design" as the first keywords related to 2016, indicating the beginning of research in these fields. For the middle spectrum, between 2017 and 2018, keywords like "seismology", "structural design", "walls (structural partitions)" and "lamination" are highlighted. These keywords express the interest of academic authors in the understanding of the general mechanics of CLT as a construction material; and, peculiarly, keywords in the late years, near to 2019, are closer to dedicated or specific mechanics of the material; for instance, "shear walls", "shear strength", "bending stress" and "finite element method". In addition, keywords such as "life cycle", "global warming", "energy efficiency", and "environmental impact" have a meaningful appearance in the last years, showing how construction is moving towards a sustainable industry and how this industry considers Cross-laminated timber as an alternative sustainable material.

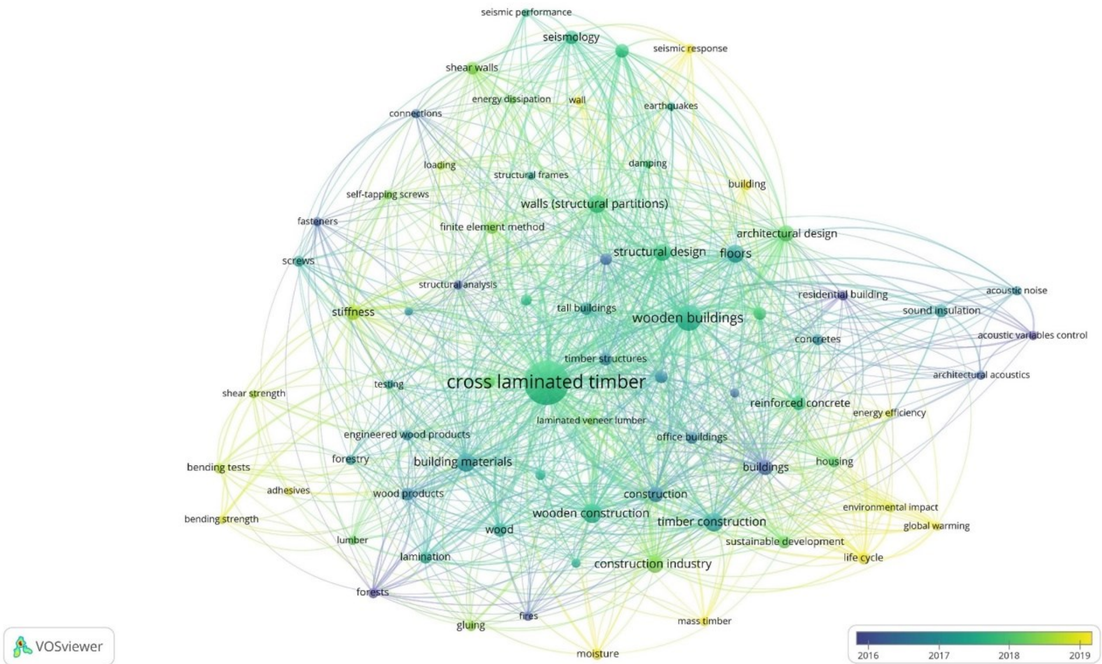


Figure 2-4. Time-based network of co-occurring keywords showing the evolution of nodes based in the average year for CLT in construction

2.3.3. Coauthor Co-occurrence Analysis

The academic data obtained from Scopus has multiple properties available from the articles, including the information of the authors; then, we could make an analysis of the principal researchers working in this field and the collaboration among them. Thus, a network map similar to the keywords can be generated but for co-authorship instead. Table 2-3 shows the first top 10 leading researchers in this field, using the number of publications in the dataset; where M. Shahnewaz (Fast + Epp & University of Northern British Columbia), C. Loss (University of Northern British Columbia), and A. Polastri (National Research Council of Italy) are listed as the first three positions.

Table 2-3. List of the top 10 most productive authors in the 2006-2022 time period for CLT in construction.

Author	Institution	Country	Count	Percentage
T. Tannert	University of Northern British Columbia	Canada	18	2.390%
S. Pei	Colorado School of Mines	USA	15	1.992%
De. Van	Colorado State University	USA	12	1.594%
Ar. Barbosa	Oregon State University	USA	10	1.328%
A. Sinha	Oregon State University	USA	9	1.195%
I. Smith	University of New Brunswick	Canada	8	1.062%
M. Popovski	FPInnovations	Canada	7	0.930%
X. Li	Deakin University	Australia	6	0.797%
A. Polastri	National Research Council of Italy	Italy	6	0.797%
M. Fragiacomo	University of L'Aquila	Italy	6	0.797%

Network maps are helpful for visualizing and analyzing academic data because authors can capture the logic and behavior in the body of knowledge [43] . Otherwise, they will have to rely on their reading and biased systematic reviews. It is necessary to use visualization tools for this purpose. CiteSpace allows the user to generate maps different from keyword networks [43] , which are needed to scrutinize the extensive amount of data from the academic dataset, making CiteSpace an advantageous software for scientometric analysis. Thus, this instrument was used to obtain and evaluate the network map for co-authorship, country co-occurrence, co-citations, and abstract clustering. In addition, CiteSpace allows showing a burst detection graph based on Kleinberg's work, which helps detect the frequency of abrupt change in a specific time gap of any entity [44].

The network map for co-authorship is presented in Figure 2-5. Each node represents an author, and the link among them is the collaboration or the so-called co-authorship in publications. Not all the authors are shown in the picture to maintain cleanliness, and the number of nodes was reduced through pathfinder, a recommendation by the author of CiteSpace [45] . The map generated possesses 338 nodes and 414 links. The size of each node is proportional to the author's number of publications. The thickness of the link is linked to the level of collaboration between researchers; see Table 2-4 for the general parameters of this graph. Among the multiple parameters given by CiteSpace, modularity Q and mean silhouette helps in understanding the frame properties of the network. First, modularity Q, measuring the quality of grouping in a network, has a high coefficient (0.7856), meaning that the map generated is well spread in loose groups [46] . The second parameter, mean silhouette, has a coefficient of 0.9443, meaning that the clusters found in the network are well-defined or heterogeneous [47] .

Table 2-4. General parameters of the co-authorship network.

Network	Nodes	Links	Density	Modularity Q	Mean Silhouette Score
Co-authorship	338	414	0.0073	0.7856	0.9443

As shown in Figure 2-5, the authors with more collaborations are displayed with a bigger circle in their node than the others; the bigger the size, the strongest the collaboration, where researchers like T. Tannert, J. W. van de Lindt, S. Pei, and A. Barbosa represent the lead circle of authors. Nevertheless, even the strongest researcher covers less than 3 percent of the publications for CLT in construction, meaning that more international academic teamwork will benefit this field. On the other hand, using the "centrality" parameter, defined as a function of the sum of all the minimum distance between a node and all others [48] , we could see that T. Tanner (centrality = 0.12) has the highest score in this network. Yet, this number is incredibly small and suggests more collaborations again among researchers. Now, it is possible to find other critical contributors by using the burst detection tool in CiteSpace, where the author burst identifies entities with a high number of citations in a small period of time. The results show that S. Gagnon (burst strength: 1.78, 2009 - 2013) and I. Smith (burst strength: 1.72, 2014 - 2018) had a burst of 4 years; however, A. Polastri (burst strength: 2.54, 2016 - 2018) and R. Brandner (burst strength: 2.54, 2016 - 2018) had a stronger burst in half their time. These contributors had great attention in their period of time, and it is worth mentioning S. Liang (burst strength: 1.99, 2020 - 2022) and H. Gu (burst strength: 1.59, 2020 - 2022), who are rising to be lead authors in this field in the last 2 years. The fact that these two last authors have been researching in this field in the last years means the importance of CLT in construction, but the centrality metric and the node sizes still suggest higher collaborations among researchers.

Figure 2-5. Co-authorship network map for academic articles for Cross-laminated timber in construction.

2.3.4. Network of countries/regions and institutions.

A network was created to visualize how research publications on cross-laminated timber for construction are distributed in different countries. This network is made up of 51 nodes and 95 links. In Figure 2-6, it is shown 5 countries with the highest contribution of publications in this area; the USA with 77 articles, where the authors who contributed the most cited articles are Shiling Pei, Ryan Ganey, and Omar Espinoza; Canada with 68 articles, in the country the most cited authors are Lin Wang and John W.van de Lindt; Italy with 48 articles, where the top authors are Cristiano Loss and Thomas Reynolds; and, China with 42 articles, its most relevant authors are Minjuan He, Haibo Guo and Ying Liu with the most cited papers in the research field. In the Citespace tool, nodes have centrality levels in the interval [0,1]. Nodes with high centrality are represented with an outer purple ring, indicating that they are connected to at least two or more large groups of nodes. (Referencia). In this analysis that can be seen in Fig.6, it is shown that the countries with a key position are: Austria (centrality = 0.31), Canada (centrality = 0.31), Italy (centrality = 0.29).

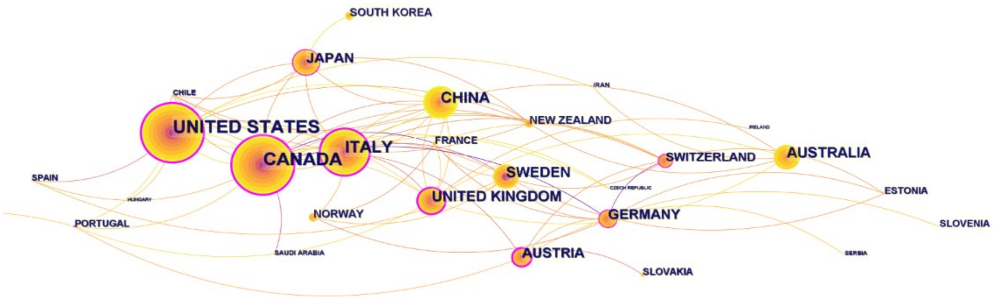


Figure 2-6. Network of countries/regions for publication of CLT in construction from 2006 to 2022.

When there is a sudden high increase in research over a period of time, in Citespace, it is indicated as a citation burst, see Figure 2-7. Aside from Switzerland, the rest of the countries have not heavily researched Cross-laminated timber in construction for more than two years. However, it is noticeable how all the nations have given importance to this field since 2016, matching with the integration of CLT as a primary structural element in 2015 for the International Building Code (IBC). In Figure 2-7, it can be seen how from 2016, the research focus began to increase, leaving the latest bursts from 2020 until today's year (2022). Furthermore, the institutions' contributions regarding cross-laminated timber for construction were also identified. The institutions/faculties most involved and active in publications are The University of Auckland with (28 publications), the University of Trento (22 publications), and RMIT University (19 publications).

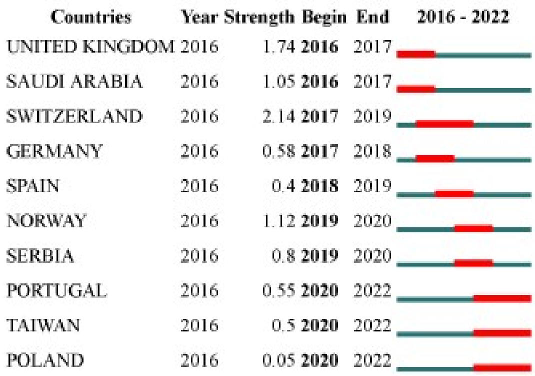


Figure 2-7. List of the relevant countries with citation bursts in the 1999–2019 time period.

2.3.5. Author Co-citation Network

A co-citation network was generated to visualize the most important authors in the research area on cross-laminated timber for construction. Figure 2-8 shows the network made up of 281 nodes and 777 links. In this representation, each node means the number of times each author has been cited. The links generated between each author speak for the collaborations made between the authors. The authors identified as the most relevant in this network are Thomas Tannert, with 18 research collaborations that have a total of 175 citations; Shiling Pei, with 15 articles that have received a total of 429 citations; John W. van de Lindt, with 13 records and a total of 341 citations.

Moreover, regarding the top 10 most cited authors represented between 2006 and 2022 in Figure 2-9, a particular case can be observed where Sylvan Gagnon, with only 3 articles, had one of the longest bursts, with a duration of 4 years. This is directly related to the low level of importance that existed in the area of CLT panels in the construction industry at that time. The peak had not yet arrived, and this area was only started to be slightly investigated, for which, despite the fact that Gagnon did not contribute a large number of articles, his contribution was one of the first and most relevant to further research in the area of cross-laminated timber for construction.

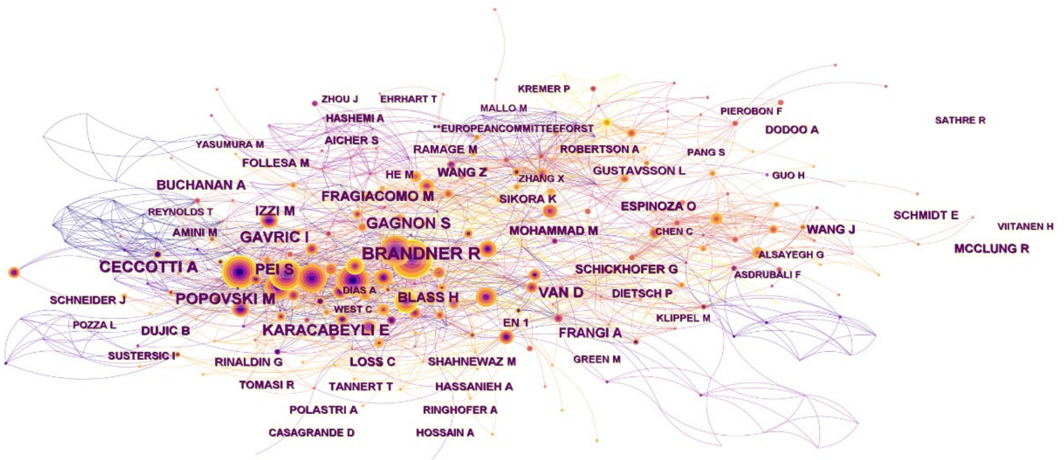


Figure 2-8. Author co-citation network for publications of Cross-Laminated Timber in construction.

Authors	Year	Strength	Begin	End	2006 - 2022
LAM F	2006	1.77	**2008**	2013	
GAGNON S	2006	1.79	**2009**	2013	
LEHMANN S	2006	1.9	**2012**	2013	
POLASTRI A	2006	2.13	**2016**	2018	
BRANDNER R	2006	2.02	**2016**	2018	
BLOMGREN H	2006	1.59	**2016**	2017	
BERMAN J	2006	1.59	**2016**	2017	
VAN D	2006	2.42	**2017**	2019	
LIANG S	2006	1.96	**2020**	2022	
SUBHANI M	2006	1.56	**2020**	2022	

Figure 2-9. List of the top authors with relevant co-citation bursts.

2.3.6. Journal Co-citation Network

For a better understanding of the research of cross-laminated timber in construction and as a complement to Table 2-1, where the leading academic journals and conference proceedings were identified from the Scopus data, a journal co-citation network map was generated with a result of 535 nodes and 2458 links, see Figure 2-10.

The node's size represents the co-citation frequency for journals or conferences in this map. The most prominent entities were *Construction and Building Materials* (frequency of 120), *Engineering Structures* (frequency of 102), *Journal of Structural Engineering (United States)* (frequency of 83), *Energy and Buildings* (frequency of 50), *Building and Environment* (frequency of 59), *European Journal of Wood and Wood Products* (frequency of 47), *Journal of Materials in Civil Engineering* (frequency of 39), and *Sustainability (Switzerland)* (frequency of 37). The results are pretty similar to the top sources for CLT in construction. Peculiarly, the centrality was calculated, and the three top journals changed compared to the frequency table. The first entity was World Conference on Timber Engineering, the second was International Association for Bridge and Structural Engineering (IABSE), and the third was Engineering Structures. This result suggests that conference proceedings are highly used by researchers, where conference articles cite other academic journals; however, academic journals do not often cite conference proceedings. It is worth mentioning that the journals related to Cross-laminated timber in construction are mainly focused on structural research, followed by material engineering and others with worthy participation in sustainability.

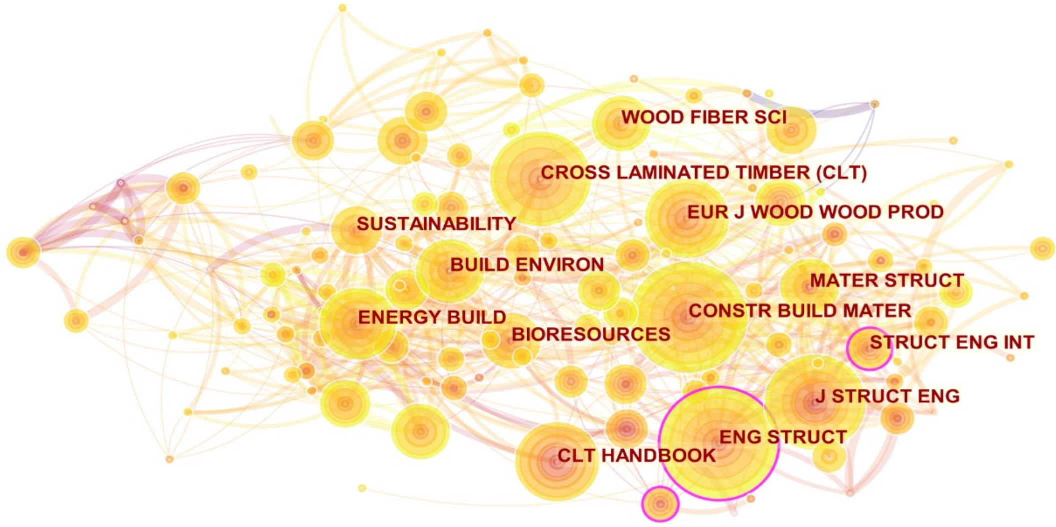


Figure 2-10. Journal co-citation network map related to Cross-laminated timber in construction.

2.3.7. Document Co-citation Network and Clustering.

The subsequent analysis is document co-citation, which helps understand the relationship of one entity among others, academic articles in this case. This analysis allows us to understand the base knowledge structure and determine the quantity and relevance of references used by researchers. The network map was generated on CiteSpace, as shown in Figure 2-11. Additionally, CiteSpace allows you to sort the publications, and the most relevant list is presented in Table 2-5. Here the article from Brandner stands out from the rest of the journals with 56 citations and a centrality of 0.20, represented with a more significant node and a purple outer ring in Figure 2-11 [49] Click or tap here to enter text.. Yet, in general, all the documents have low centrality, meaning that there is no document central to the entire research field. To consider a publication central to the network, it must have a value above 0.3 [50] .

Table 2-5. List of the top 25 most cited articles between 2006 and 2022.

#	Article	Total Citations	Centrality	#	Article	Total Citations	Centrality
1	Brandner et. al. [49]	56	0.20	14	McClung et. al. [51]	6	0.03
2	Ramage et. al. [52]	12	0.02	15	Ehrhart et. al. [53]	6	0.00
3	Espinoza et. al. [54]	11	0.03	16	Gavric et. al. [55]	5	0.01
4	Sikora et. al. [56]	11	0.02	17	Wang & Ge [57]	5	0.01
5	Gavric et. al. [58]	9	0.15	18	Aicher et. al. [59]	5	0.01
6	Asdrubali et. al. [60]	9	0.04	19	Bita & Tannert [61]	5	0.03
7	Liao et. al. [62]	8	0.02	20	Hassanieh et. al. [63]	5	0.01
8	Gagnon et. al. [5]	8	0.09	21	Ceccotti et. al. [64]	5	0.01
9	Izzi et. al. [65]	8	0.04	22	Shahnewaz et. al. [66]	4	0.01
10	Karacabeyli & Gagnon [67]	7	0.14	23	Amini et. al. [68]	4	0.05
11	Schmidt et. al. [69]	7	0.01	24	He et. al. [70]	4	0.00
12	Pierobon et. al. [71]	7	0.01	25	Morandi et. al. [72]	4	0.00
13	Jones et. al. [73]	6	0.00				

As shown in Figure 2-11, the document co-citation map has 491 nodes and 1353 links, and it includes the clusters generated by the abstract terms. In this graph, each node represents a journal or conference proceeding where the label is taken with the first author's name and the year of publication. Each link symbolizes the co-citation connection between two publications, and the node size is proportional to the co-citation frequency. The clusters were generated using the abstract of each journal cited, obtaining a total of 10 groups. These clusters are well defined, but four are loosely gathered around the main body in the middle of the network. Table 2-6 presents the list of the clusters, including the IDs, the label given by CiteSpace, an alternative name deducted from the principal journal abstracts, and the leading representative publications.

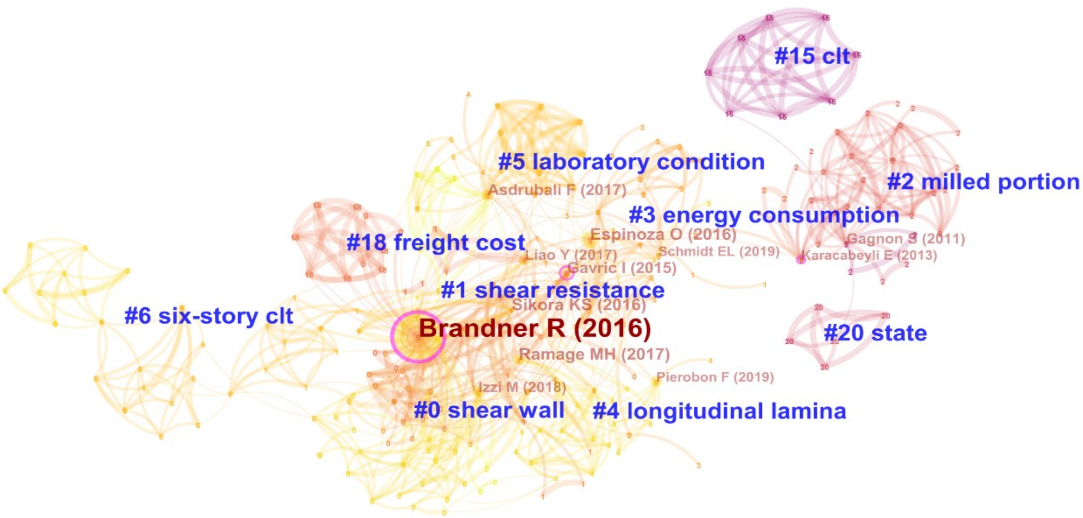


Figure 2-11. Abstract clustering network map of co-citations.

It is possible to analyze the knowledge clusters for Cross-laminated timber in construction with the data in Table 2-6 and the network map in Figure 2-11. Starting with the first clusters in the timeline, cluster #15 (mean publication year = 2009) and cluster #20 (mean publication year = 2011), these groups have a low number of publications related to them; still, it is essential to remember that academic articles were limited around that decade. There were years with only one publication associated with this field. For the same reason, there is no surprise that the first topics of researchers were related to the understanding of CLT as a new style of construction. For instance, in cluster #15, Crespell et al. made a study to understand CLT as an alternative construction material against concrete [74] ; Popovski et al., from cluster #20, made an analysis of CLT construction design according to the North American building code [75] .

Table 2-6. Co-citation clusters of Cross-laminated timber in construction from 2006 to 2022.

Cluster ID	Size	Abstract Cluster Label	Alternative Labels	Mean Publication Year	Representative Documents
#0	53	Shear wall	Seismic characteristics	2016	Polastri [76] , Brandner [49]
#1	36	Shear resistance	Rolling Shear / Structural Behavior	2016	Ehrhart [53] , Oktavianus [77]
#2	32	Milled portion	Mechanical Properties	2012	Gagnon [67]
#3	26	Energy Consumption	Time/Cost Optimization	2016	Gasparri [78]
#4	24	Longitudinal Lamina	Lamina properties	2017	Pang [79], [80]
#5	22	Laboratory Condition	Material Properties / Energy performance	2017	Asdrubali [60] , Wang [57]
#6	19	Six-story CLT	CLT in tall buildings	2017	Fitzgerald [81]
#15	8	CLT	Sustainability Comparison / CLT And Concrete	2009	Crespell [74] , Damtoft [82]
#18	7	Freight Cost	Transportation Analysis	2015	Passarelli [83]
#20	5	State	North America state	2011	Popovski [75]

The rest of the clusters are dedicated to understanding the mechanical properties and sustainability of Cross-laminated timber in construction. The bigger group, cluster #0, focuses on seismic performance analysis in CLT, and part of the reason for this center of attraction is the growing usage of CLT in high-rise buildings (colloquially called “tall timber buildings”) [76] . A clearer path of the growth of CLT in buildings begins with the seismic analysis made by Ceccoti in 2008 for a 3-story building [84] ; followed by Polastri et al. who studied the seismic performance in a 7-story building with CLT core and shear-walls [76] ; and then, Connolly et al. with its publication for the UBC Tall Wood Building which has a height above 53 meters, getting the name of the world's tallest hybrid wood-based building by 2016 [85] . On the other hand, cluster #4 was dedicated to studying specific properties of CLT and the material behavior depending on the lamina composition. The authors were looking to understand the limits and behavior of the wood panels depending on their usage. For example, Pang conducted two studies, one to understand the bending strength and stiffness depending on the number of lamina combinations, wood's type, and thickness [79] ; the second study was on the analytics of the compressive resistance of CLT depending on the different grade lamina to have a more reliable way of prediction [80] .

In the area of sustainability, there is cluster #5, where we could see how researchers were seeking a more environment-friendly solution for construction, and wood came as an evident response due to its excellent strength-to-weight ratio. The studies were initially on any wood variables, softwood, hardwood, and composites, but CLT stands up against others, and an understanding of its properties is needed. For this reason, Asdrubali et al. conducted a study to gather multiple characteristics of CLT, like thermal, acoustic, and structural properties [60] ; and Wang et al. conducted a hygrothermal performance analysis to understand the long-term durability of CLT panels [57] . Additionally, cluster #18 gathered studies about the freight cost and its environmental impact. In this field, Passarelli researched the freight cost and environmental impact of transportation from the cradle up to the construction site, concluding that the CLT manufacturing plant must be as close as possible to the wood sources to reduce any low value-added product and freight cost [83] .

2.4. Results for Industry 4.0 in Construction

In the previous chapter, a review of the development of Cross-laminated timber in construction was done through a scientometric analysis. Here it was found the importance of the material in the last decade and how the authors have taken plenty of interest in this field. The main research topics are dedicated to understanding the material and its mechanical properties as detected in the co-citation clusters, and some authors explored issues related to sustainability. Oddly, nothing was found associated with Industry 4.0, which has taken a great interest in the construction industry in the last decades [86] . Topics like automation, machine learning, or cyber-physical systems were expected to appear in the inquiry, but it did not go as expected. For this reason, a brief scientometric analysis for the Industry 4.0 in construction will be done to see the big picture of the research topics in this field. As a note, in the following chapter, definitions already written in previous sections as co-occurrence, centrality, or co-citation will be avoided for the cleanliness of the article.

2.4.1. Data Acquisition

Similar to the previous analysis the data was obtained from Scopus, where the keywords used in the inquiry were *"industry 4.0"* and *"construction"*; the search was limited to the engineering field; the period was maintained to keep coherence from 2006 to 2022, and the document type was limited to journals and conference proceedings. Once the files were ready, and after a manual clean-up, the number of publications was 567 documents. The academic journals and conference proceedings were plotted in a timeline to see the interest of researchers in this field, graph presented in Figure 2-12. This figure shows a clear upward trend of publications, confirming the expected appeal of researchers in Industry 4.0 in construction. More interesting is that the inflection point occurs in a similar period as CLT, around 2016. Before continuing, it is essential to mention that an inquiry in Scopus was made, including the keyword *"cross-laminated timber"*, but surprisingly, the results gave only two journals. The first paper from Biaconi et al. used generative models and evolutionary principles for an algorithm that allows the mass customization of single-family size houses using CLT [87] . His method allows having an automated design of small buildings of CLT and helps architects and engineers to reduce the developing time of this type of project. The second article, from Colella and Fallacara, made a case study of a CLT house in the Mediterranean, Ecodomus, where they implemented intelligent design techniques and digital manufacturing tools for the building; and made an apparent necessity of new technology for mass customization [88] .

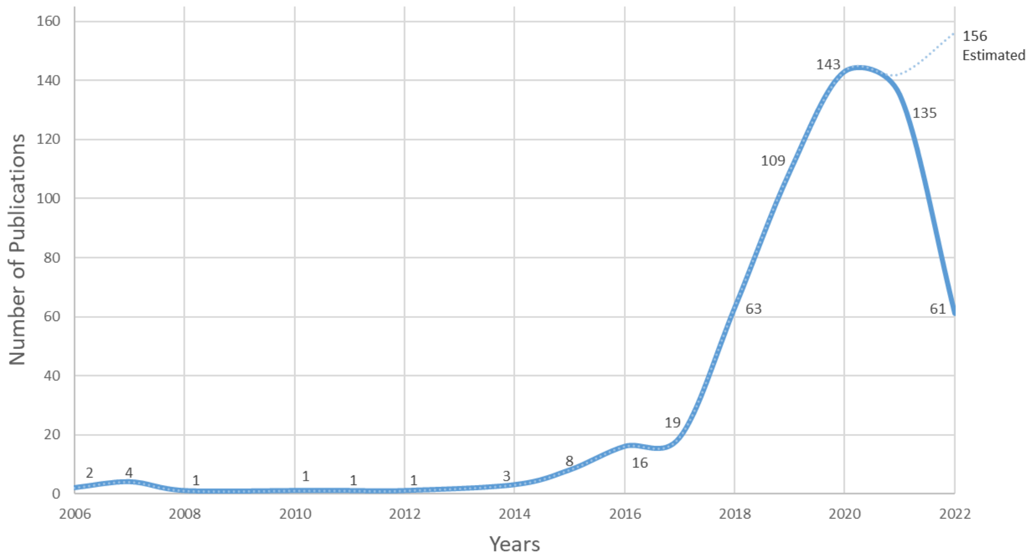


Figure 2-12. Historical trend of published studies in Industry 4.0 for construction (period 2006–2022).

The top 10 journals and conference proceedings were obtained from the academic dataset, similar to the previous chapter, and the list is presented in **Table 7**. The journals with more coverage on topics of Industry 4.0 in construction are *Buildings*, *Applied Sciences (Switzerland)*, *Automation in Construction*, and *Smart and Sustainable Built Environment*. On the conference side, the entities with more coverage are the *International Symposium on Automation and Robotics in Construction*; *International Seminar on Industrial Engineering and Management*; *Annual Conference of the International Group for Lean Construction*; and *Smart Structures and NDE for Industry 4.0*, *Smart Cities*, and *Energy Systems*. In contrast to **Table 1**, the publishers do not surpass more than four percent either in journals or conference proceedings; for instance, the leading conference covers only 3.14 percent of the publications, while on the other hand, the WCTE conference had almost half of the entire population for CLT in the construction. This means that no entity has obtained a strong position yet in this field, and the publications are still published homogenously. Additionally, it is worth mentioning that Switzerland has appeared as a leading country for journals in both tables, *Applied Sciences (Switzerland)* for Industry 4.0 and *Sustainability (Switzerland)* for Cross-laminated timber.

Table 2-7. List of the top 10 academic journals and conference proceedings from January 2006 to March 2022coverins publications related to Industry 4.0 in construction.

Journal Title	**Number of articles**	**% Total Publications**
Buildings	12	3.82%
Applied Sciences (Switzerland)	10	3.18%
Automation in Construction	10	3.18%
Smart and Sustainable Built Environment	9	2.87%
Structural Integrity	8	2.55%

Construction Innovation	7	2.23%
IEEE Access	6	1.91%
IEEE Transactions on Industrial Informatics	6	1.91%
Advances in Science, Technology and Innovation	5	1.59%
Energies	5	1.59%
Conference Title	**Number of articles**	**% Total Publications**
International Symposium on Automation and Robotics in Construction	8	3.14%
International Seminar on Industrial Engineering and Management	6	2.35%
Annual Conference of the International Group for Lean Construction	6	2.35%
IEEE International Conference on Automation/23rd Congress of the Chilean Association of Automatic Control	5	1.96%
Smart Structures and NDE for Industry 4.0, Smart Cities, and Energy Systems	5	1.96%
International Conference on Flexible Automation and Intelligent Manufacturing	5	1.96%
Annual Conference on Association of Researchers in Construction Management	4	1.57%
World Tunnel Congress	4	1.57%
International Conference on Innovation in Engineering	3	1.18%
International Workshop on Intelligent Computing in Engineering	3	1.18%

2.4.2. Keyword Co-occurrence Analysis

Once the data was obtained from Scopus and the quick analysis of the journals and conferences was done, the software VOSviewer was used to plot the keyword network for Industry 4.0 in construction. The threshold was set to 13 minimum occurrences in this network, obtaining 56 of the 4733 keywords. Like the previous analysis, the threshold was set after different iterations to find the optimal network. Figure 2-13 displays the network for the co-occurrence keywords. This map has 56 nodes, 994 links, and a total link strength of 3209. As shown in Table 2-7, the two keywords with high occurrences after "industry 4.0" and "construction industry" are "internet of things" and "architectural design", highlighting the topics authors have used the most in this field at this date. An additional parameter given by the VOSviewer is the average year of publication. Looking at Table 2-7 with the most relevant keywords, it is possible to see that all of them have taken relevance in the last three years, from 2019 to 2021. This matches with the trend found in the historical graph in Figure 2-12. Moreover, keywords such as "life cycle" and "sustainable development" surface in this analysis, similar to CLT results, meaning that sustainability is a topic of interest in both fields.

Table 2-8. List of selected keywords and relevant network data for Industry 4.0 in construction.

Keyword	Occurrences	Average Year Published	Links	Total Link Strength
Industry 4.0	322	2020	55	839
Construction industry	157	2019	54	535
Internet of things	52	2020	47	197
Architectural design	48	2020	49	254
Embedded systems	42	2020	51	200
Manufacture	39	2019	41	124

Industrial revolutions	38	2020	45	166
Automation	37	2019	46	122
Life cycle	33	2019	44	143
Decision making	32	2020	41	109
Digital twin	31	2021	44	131
Industrial research	31	2020	45	128
Project management	31	2020	39	115
Building information modelling	29	2020	39	122
Artificial intelligence	27	2020	40	102
Robotics	27	2020	36	105
BIM	26	2020	32	94
Augmented reality	25	2020	34	72
Sustainable development	24	2020	41	100
Machine learning	23	2020	35	79
Design/methodology/approac h	22	2021	38	108
Smart manufacturing	22	2020	27	64

It is possible to see that “industry 4.0” and “construction” are the most relevant keywords in Figure 2-13. They are positioned in the center of the map, are bigger in size, and the rest of the keywords emerge from the two of them. It is interesting how a new keyword, “construction 4.0” was generated from the interaction of these two fields. However, this node is still tiny compared to the other nodes, meaning this new definition is still in development. The co-occurring map presents the keywords in colour code depending on the clusters of the entities; 5 groups were detected in this network. The yellow set is the first group to review where the keyword “bim” is mentioned in multiple nodes, and “architectural design” escorts them. BIM is an acronym from the software “Building Information Modeling”, and it is a tool heavily used in construction in the last years because of its smart features, like 3D modelling, cloud storage, information sharing, and others [41], [89] Click or tap here to enter text.. In the green cluster, topics related to data analysis are gathered, and those such as “smart manufacturing”, “cyber-physical system”, “machine learning” and “artificial intelligence” cover the main topic. Curiously, the keyword “robotics” is placed in this cluster. However, it is positioned right next to the blue group, which covers issues related to the manufacturing industry like “automation”, “industrial research”, “3D printing” and “manufacture”. A brief look at the map allows realizing that the “manufacture” node emerges from the “industry 4.0” node, and the two topics, “robotics” and “automation”, bifurcate from it. Figure 2-14 displays the time-based network in addition to the co-occurring map, where the color code represents in yellow the latest developed nodes and purple for the oldest topics. It is worth mentioning that even the oldest keyword in this figure is from 2019, meaning that its relevance still prevails. “digital twin”, “artificial intelligence”, “blockchain” and “construction 4.0” are the leads in the most recent keywords, and represent the latest interest of researchers as well as showing how the definition of construction 4.0 is still in its development. On the other hand, “3d printers”, “manufacturing industries” and “office buildings” are the oldest keywords from this map or the first topics authors considered worthy of investigation in this field.

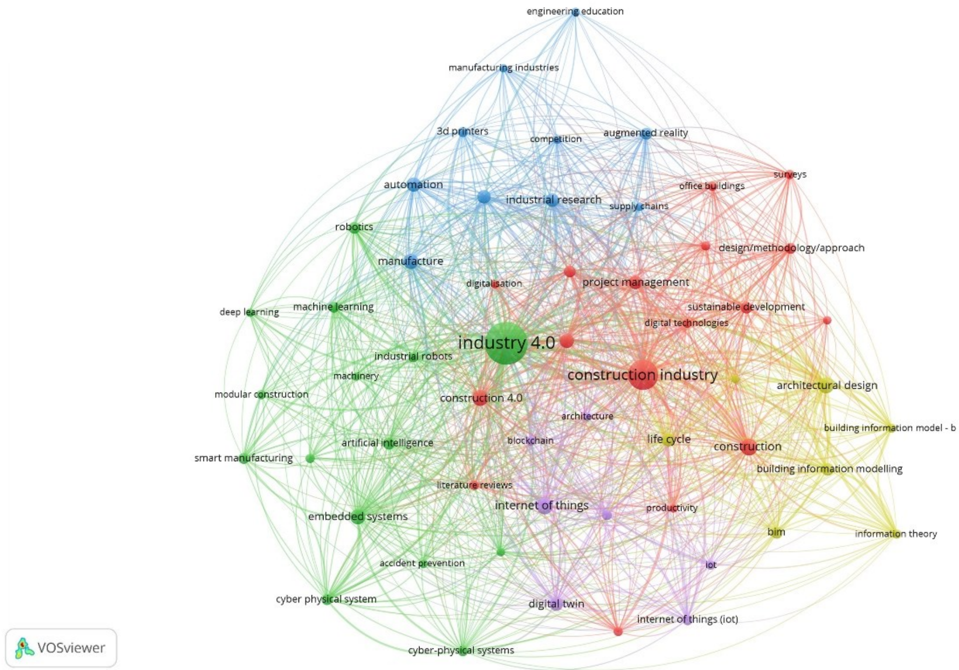


Figure 2-13. Network map of co-occurring keywords for Industry 4.0 in construction (2006-2022).

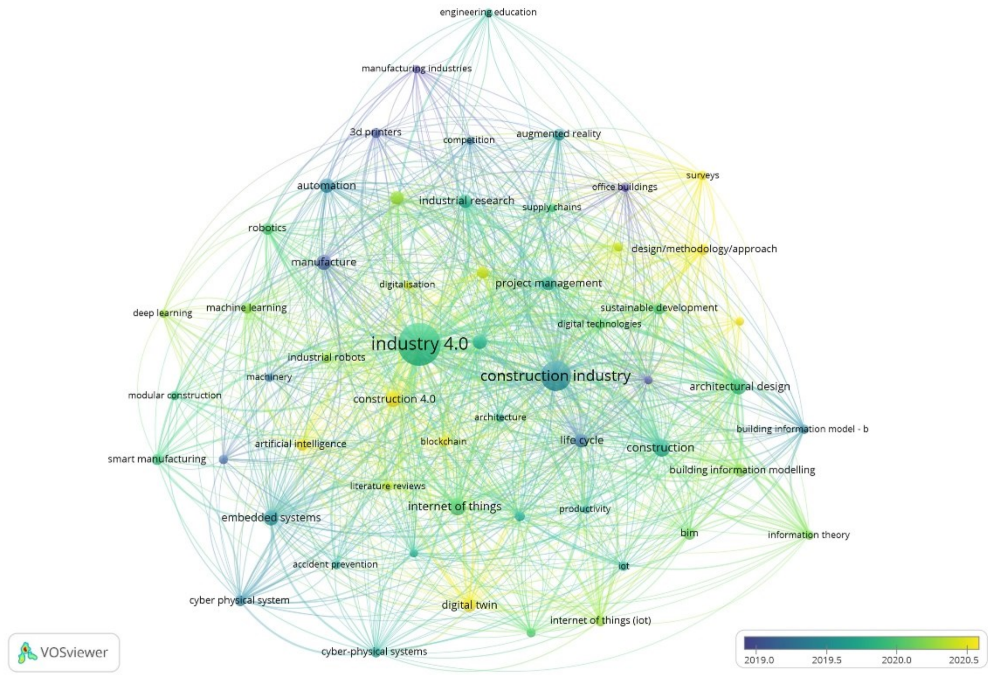


Figure 2-14. Time-based network map of co-occurring keywords showing the development of nodes based on the average year for Industry 4.0 in construction.

2.4.3. CiteSpace Network Maps

The scientometric analysis for understanding the trending knowledge for Industry 4.0 in construction was done lighter than in the previous section. The reason behind that is the vast amount of topics Industry 4.0 could cover, and doing extensive research in this area will push the study out of the scope of this article. What is intended in this study is to find trends and research gaps in the intersection among Cross-laminated timber, Industry 4.0, and the construction industry. Therefore, not all network maps were implemented, and some even provided negligible information. For example, contrary to the CLT analysis, the co-authorship network map for Industry 4.0 is not suitable for this study because the result given by CiteSpace shows a scattered network where it is hard to find nodes and connections. These results suggest that only certain authors have worked together in publications, highlighting an opportunity for the academic community in this field. From the small list obtained, the first author with seven documents is Dominik T. Matt [90] , and the second with five publications is Patrick Dallasega [91] . Both researchers belong to the Free University of Bozen Bolzano in Italy.

A journal co-citation network was made to understand the journals with more importance related to Industry 4.0 and construction. CiteSpace generated a network map with enough homogenous balance on all the nodes, but the critical information is present in the cited journal list. In this list, the leading cited journals are as follows: *Automation in Construction* (Count of 96 & centrality of 0.12), *Procedia CIRP* (Count of 61 & centrality of 0.08), *Applied Sciences (Switzerland)* (Count of 33 & centrality of 0.09), *Buildings* (Count of 26 & centrality of 0.0), and *IEEE access* (Count of 23 & centrality of 0.03). From this list, a burst analysis was generated where the entity with higher strength is *Procedia CIRP* with 4.51 between 2017 and 2018, followed by *Applied Sciences (Switzerland)* with a burst strength of 3.36 from 2018 to 2019. The rest of the journals did not present a considerable strength, but it is worth mentioning that the remainder of the list has a presence after 2016. Additionally, the centrality was calculated for all the documents. All the results came with values below 0.15, meaning that there is still no journal or conference that is central to the research in this field.

The following network map created was for countries or regions, as seen in Figure 2-15. This map has 18 nodes and 174 links. The five leading countries with publications on Industry 4.0 in construction go as follow: the United States has the first position with 52 documents and its top authors are Bing Qui from the University of Florida and Konstantinos Mykoniatis from Auburn University; the second leader is Italy with 39 publications where Gabriele Pasetti Monizza from Free University of Bozen-Bolzano, and Fabio Bianconi from University of Perugia are the top authors; the third position is taken by Germany with 38 journals where Viktor Mechtcherine from Technische Universität Dresden and Xi Chen from Fraunhofer Institute for Manufacturing Engineering and Automation are the lead authors; the fourth place is for China with 33 documents, where its leading researchers are Keliang Zhou from Wuhan University of Technology, and Heping Xie from Shenzhen University; and the fifth position is taken by Malaysia with 29 publications where Wesam Salah Alaloul from University Technology PETRONAS, and Raihan Maskuriy from Malaysia Japan International Institute of Technology are the leading researchers. In terms of centrality, the United Stated has an outstanding record of 0.55, positioning this nation as a central entity for Industry 4.0 in construction. Unsurprisingly, “USA” is the only node in the center of the map with the purple outer ring to highlight its centrality. Contrary to this position is Germany which, even though that has a high number of publications in this field, its node is isolated and aside from the main body of nodes in the network. This suggests that the German academic society should collaborate with other countries.

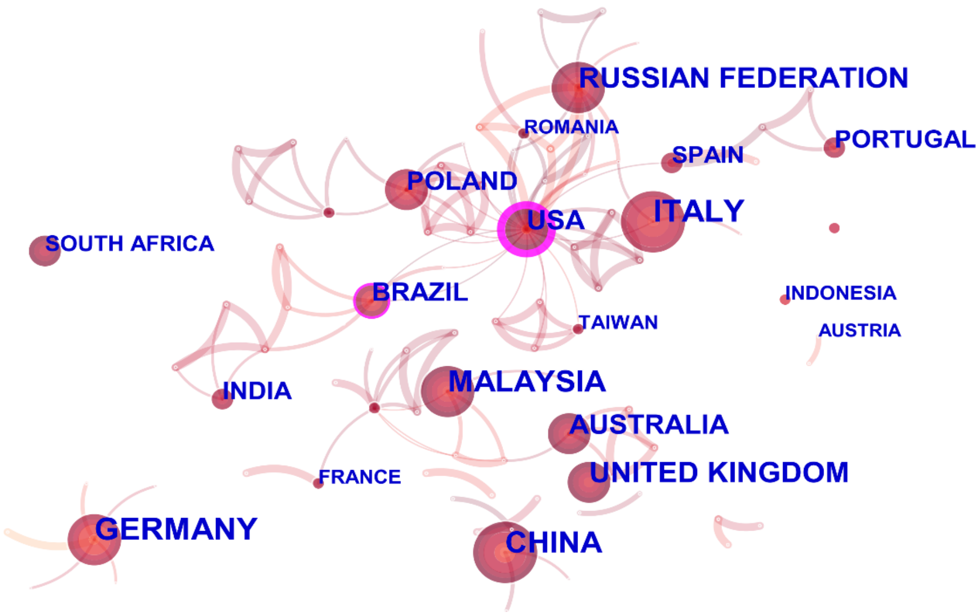


Figure 2-15. Network of countries/regions for publication of Industry 4.0 in construction from 2006 to 2022.

Also, a co-citation network map was created for the authors working on topics related to Industry 4.0 in construction. This network intends to detect the most influential researchers in the field. The map is presented in Figure 2-16 with 458 nodes and 1764 links. The leading authors from the network go as follow: the first position is taken by Thuy Duong Oesterreich from Osnabrück University with 40 citations; the second position is for Patrick Dallasega from the Free University of Bolzano with 37 citations; on the third position, Jay Lee from the University of Cincinnati with 34 citations; Henning Kagermann is taking the fourth position with 28 citations; and, Xiao Li takes the firth place from The Hong Kong Polytechnic University with 25 citations. The author's diversity shows how broad the research on Industry 4.0 in construction has been. Additionally, the centrality was calculated for all the nodes, but none had a score above 0.2, meaning that there is no author central for this field yet. Similarly, no author has shown enough strength or length in the citation burst, and the only worthy note is that all of them started to appear in the table after 2017.

The final network map is the document co-citation network displayed in Figure 2-17. This map has 350 nodes and 830 links, and 5 clusters generated with the abstract terms of the publications. The network for Industry 4.0 in construction appears more scattered than in the previous analysis, and even the number of clusters is around half of the preceding result. Only the top four authors surpass ten citations. The first leading author is Patrick Dallasega (frequency of 22), who did a schematic literature review looking to improve the construction supply chain with the concept of proximity [92] Click or tap here to enter text.; the second author is Thuy Duong Oesterreich (frequency of 21), who made a literature review for the state of digitalization and automation in construction [93] ; the third place is taken by Anil Sawhney (frequency of 11) who published a book for the framework of industry 4.0 in construction [94] ; and finally, Roy Woodhead (frequency of 10) takes the fourth place with a literature review of IoT (Internet of Things) systems in construction [95] . Like the previous networks for Industry 4.0 in construction, the centrality of the nodes for the co-citation map is negligible. There was no cited document with a burst of more than two years or with enough strength.

Clusters were generated in the co-citation network using the abstract term, and the results of the five elements are placed in Table 2-9. The group bigger in size, #0, covers literature reviews on the state of Industry 4.0 in the construction field. Curiously, the more representative authors are Dallasega and Woodhead, who made it top of the co-cocitation network. This cluster covers all kinds of reviews for different trending topics in Industry 4.0, for instance, IoT, digital twins, cyber-physical systems, or smart factories. Nevertheless, the journals found in this cluster do not investigate the topic profoundly, and they only seek to understand the current advances in construction. The second cluster, #1, is named "smart factory" or the alternative label is "case study". In this cluster is possible to find journals in case studies related to "smart" factories or manufacturing; an example is the work of Al-Seed, where digital objects were used in building information modelling (BIM) to simulate the automation of manufacturers in the construction industry [96] . Another instance is the work of Li, who used RFID and BIM technology, and improved the schedule performance of prefabricated house construction (PHC) [97] . In the third cluster, #2, the topic covered is "digital twin," where the documents gathered cover multiple issues related to this technology. Yet, it is essential to mention that numerous journals mention BIM as one of the critical tools in digitalization and digital twin development for construction. Here it is possible to find studies like Shirowzhan et al., who studied the BIM applications and their compatibility in the construction industry and multiple levels of typical companies [98] . The fourth cluster, #4, is dedicated to journals researching data usage in construction. Some authors suggest the introduction of blockchain to improve the supply chain, while others pretend to use big data for decision-making. Lastly, the fifth cluster, #6, gathers journals related to the digitalization of different areas in construction, where BIM is mentioned again. For instance, Bortolini et al. made use of

BIM to improve the logistics planning and control for customized prefabricated buildings [99] .

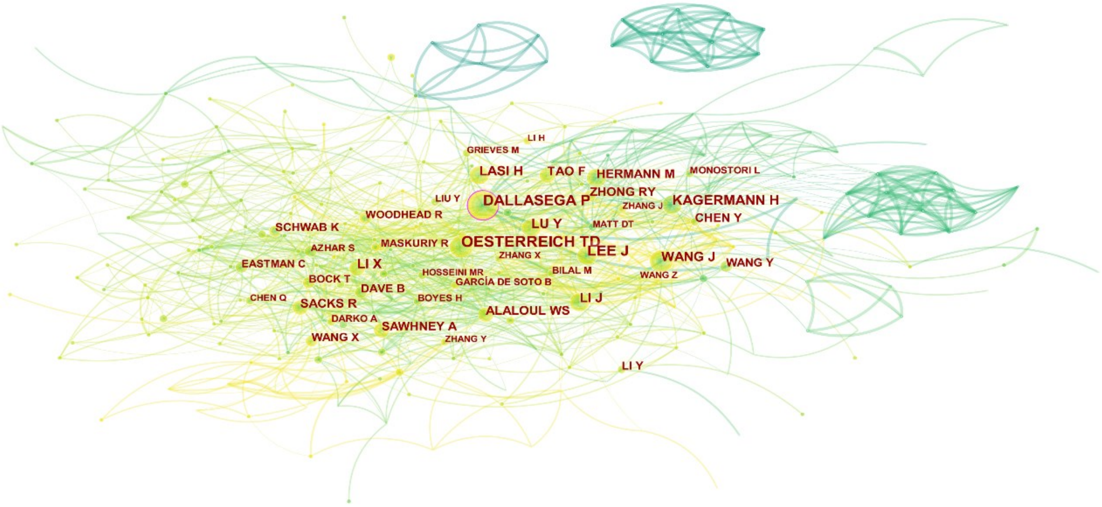


Figure 2-16. Author co-citation network for publications related to Industry 4.0 in construction.

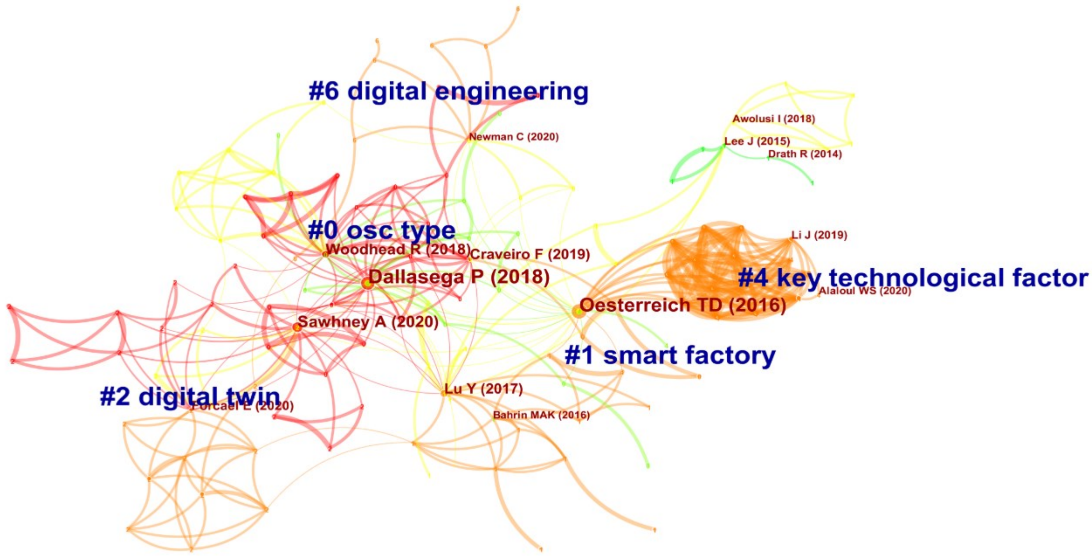


Figure 2-17. Abstract clustering network map of co-citations for Industry 4.0 in construction.

Table 2-9. Co-citation clusters of Industry 4.0 in construction from 2006 to 2022.

Cluster ID	Size	Abstract Cluster Label	Alternative Labels	Mean Publication Year	Representa ve Documents

#0	40	OSC type	Literature review	2018	Dallasega [91] , Woodhead [95]
#1	29	Smart factory	Case study	2016	Al-Saeed [96] , Li [97]
#2	25	Digital twin	BIM	2018	Shirowzhan [98] Click or tap here to enter text., Busswell [100]
#4	18	Key technological factor	Blockchain/information sharing	2018	Li [101] Click or tap here to enter text.
#6	10	Digital engineering	Digitalization/prefabrication	2018	Bortolini [99]

2.5. Future Trends

2.5.1. Overview

This article makes use of scientometric analysis to review the current work in the fields of Cross-laminated timber and Industry 4.0 in construction. The investigation was done in two separate sections, first covering CLT in construction and then reviewing Industry 4.0 in construction. The aim is to find the intersection among the three topics and detect possible research gaps.

The first data given by Scopus clarifies the attention acquired by Cross-laminated timber in construction in the latest years. Especially after 2015, when the IBC included CLT as a primary structural element. Following the trend from the academic publications, it is estimated that 169 documents will be uploaded concerning this field by the end of the year. Now, following the color code for the keyword co-occurrence analysis in Figure 2-3, it is possible to say that researchers have focused on four groups, structural behavior, material properties, environmental impact, and sound isolation; where structural behavior is by far the most substantial cluster and multiple keywords are related, like “structural design”, “seismic design”, and “finite element method”. On the other hand, even though Cross-laminated timber was initially developed in Europe, with origins in Austria and Germany, it is safe to say that North America (the United States and Canada) is genuinely involved in the research of this field. This note is made based on two facts. First, the leading seven most productive authors, Table 2-3, were led by researchers from these nations. Second, the USA and Canada have the bigger-sized nodes in the network map done for the countries, Figure 2-6, and their centrality score combined is superior to the rest of the nations. On the author’s co-citation network, Figure 2-8, it is possible to see that the scientists with the most collaboration are Thomas Tannert, Shiling Pei, and John W. van de Lindt, all from North America. As a complement to the note made by the keywords co-occurrence analysis, the journal co-citation network, Figure 2-10, states that the most prominent journals are those related to structural analysis and material properties, listing the top three journals as follows: *Construction and Building Materials, Engineering Structures, and Journal of Structural Engineering.* Additionally, in the document co-citation network, Table 2-5, the most-cited journal, was from Brandner et al., whose work is an overview of the material's properties, suggested design, and connections of CLT. It is understandable the high impact of his study because it was released in 2015, the year of the inflection point when CLT took relevance.

Furthermore, the clusters generated by the abstracts of the journals, Figure 2-11 and Table 2-6, indicate that the most critical field for CLT in construction has been structural behavior and mechanical properties. Considering the relevance this material has taken in North America, it is understandable how essential it was for the authors to comprehend the material for construction because the soil is completely different from the continent of origin. This is highlighted by cluster #0, which gathers over 50 journals studying the seismic characteristics of the material to understand its usage in seismic areas. Thus, with the data provided by the multiple network maps, it is feasible to state that Cross-laminated timber has increased its use in construction starting in 2015 as an effort by the researchers to reduce its carbon footprint and develop a sustainable industry. In contrast, North America has been the continent with more interest in its development, and its implementation started with short story buildings, but lately, it has been used for tall timber constructions. The effort of the authors to understand the mechanical properties of CLT has given results, and now it is possible to see construction projects like the super tall Oakwood Tower, which is looking to achieve 300 meters of height [102]Click or tap here to enter text.. On the other hand, it is apparent how dense the research effort in the structural analysis of CLT is, but at the same time, it is obvious the lack of work in other areas of research. It is conceivable to find a few journals on topics related to sustainability, but it is practically null the number of publications for topics like manufacturing or automation. Therefore, a quick analysis of the field of Industry 4.0 and construction is needed to understand the knowledge network and its trends.

The data obtained from Scopus for Industry 4.0 in construction shows an upward trend similar to Cross-laminated timber, with a different inflection point, 2017. This timing is odd, and there was no event found as an obvious point of bifurcation, but it is interesting how close the year of inflection is for both research fields. Then, even though the fourth industrial revolution had a formal origin in 2011 in Germany, it took six years for authors to consider applying these features in the construction industry [103] . The first analysis tool in this study for the Industry 4.0 was the keyword co-occurrence network map which shows five groups of interest following the color code, see Figure 2-13. Here, the most significant green group covers keywords related to the data analysis, and the second cluster covers those about the manufacturing industry, blue color. Curiously, the keyword "robotics" is included in the data analysis cluster, but it is placed on the border next to the blue group. With little more attention, it is possible to see how the "manufacture" node emerges from the industry 4.0 main point, and "robotics" and "automation" rise from this keyword.

Additionally, it is worth noting the existence of a cluster focused on BIM software, used heavily in the construction industry. In the time-based network map,

Figure 2-14, it can be seen how the latest topics are “digital twin”, “artificial intelligence”, and “construction 4.0”, giving a clue of the importance this field is taking in the construction industry. Sadly, the co-authorship network map barely shows a node with authors, meaning collaboration between researchers is needed. On the other hand, the journal most relevant to the field is “Automation in Construction” which had a frequency of 96 publications in it; and, looking at the network map for countries, Figure 2-15, it is possible to list the leading nations in the field, where the United States takes the first position, followed by Italy in second, and continued by Germany, China, and Malaysia. Here the United States stands outs against others in centrality with a score above 0.5. Thuy Duong Oesterreich is the author with more relevance in this field, and Patrick Dallasega takes the second position; see Figure 2-16 for the co-citation network. This map shows the high number of authors working in the field, but they are widely spread, meaning that there is still no single author who has taken extreme relevance. The latest map used was the co-citation network in Figure 2-17, where a significant part of the documents was spread and not connected among others. This display helps in understanding the trending topics of Industry 4.0 in construction. However, from the clusters generated by the abstract, it is noticeable how the leading group is related to literature reviews. Here all the journals are seeking the possibility of Industry 4.0 features in construction, showing how researchers are highly interested in this field but at the same time; it presents how immature the area is yet. The second cluster is related to case studies, and part of this group was expected as most of the time, each construction building is considered an induvial project, and practically there is no mass production like in the manufacturing industry. The rest of the clusters are dedicated to digitalizing multiple areas, where BIM takes a relevant position among them, and there is even research interest in prefabrication techniques. From all the network maps and tools just presented, it is possible to conclude that industry 4.0 has taken high relevance in the construction industry; however, research fields are still immature, and the authors' efforts are widely spread.

2.5.2. Future Trends

Now that both filed have been scrutinized, it was found that there are three trending areas from Industry 4.0 in construction, prefabrication, digital twin, and automation. Therefore, a deeper review of them will be done in the following section to understand the current status of these topics for cross-laminated timber. The search of journals was implemented with Scopus on three independent inquiries. The base keywords were typed as “cross-laminated timber*”, and “construction”, and the topic variation was included as “prefabrication*”, “digital twin*” and “automation”. In addition, the period was limited to the latest five years, from 2018 to 2022, and the subject area selected was engineering. Here is worthy to note that no document showed up in the inquiry for digital twin results, and the keyword was replaced by “digitalization”, attempting to get a snap on the research close to this field. The number of journals obtained was 15 for digitalization, 21 for prefabrication, and 7 for automation. These small numbers reaffirm the immaturity of the research in this field.

The results found in Scopus for prefabrication or off-site construction is the topic with the most documents, and they can be grouped into three subgroups, *mechanical behavior*, *comparative*, and *design*. There are studies about the mechanical behavior of the prefabricated sections of CLT and its performance in the entire building in the first group. Here Loss et al. analyzed the in-plane stiffness for hybrid CLT-steel floor panels [104] . His methodology made a finite element analysis and validated the simulation with a case experiment. On the other side, Mayencourt and Mueller made a cost and material optimization of CLT panels used on floors, looking at the bending behavior [105] . Their work changed the core layers and achieved an 18% weight reduction without loss in performance. Another author working to understand CLT is Orlowski, who made a study to validate design curves and strength reduction factors for post-tensioned timber-steel stiffened wall systems [106] . His article explains the finite element method used for the wall system and the experimental setup used for his validation. This work ends with design curves ready to be used to develop mid-rise buildings of hybrid timber-steel walls. Another subgroup for prefabrication is the journals focused on comparative studies. For instance, Ghafoor and Crawford compared different materials used in prefabricated residential walling systems in Australia to grasp the lowest greenhouse gas emissions (GHG) [107] . The results showed that timber-framed panels were the only material that could lower GHG by 7% compared to conventional brick veneer construction. Surprisingly, structural insulated panels (SIPs) provided 6% more GHG than brick veneers. Østnor et al. is another researcher working in comparative studies, where his case study compares Cross-laminated timber against on-site cast concrete [108] . His work made a literature review and case study to compare different properties between the two buildings, one with each material. He obtained that the CLT building had a 9.5% improvement in construction time, improved HSE, better dimensioning than concrete, and a 7% increase in the total cost. The author comments that a high percentage could enhance the cost of the CLT project in the future as the current contractors have null or little knowledge of its use. The last group of documents in the prefabrication inquiry lay under the design field. Here it is possible to find case studies where the authors show the design process for their projects. For example, Bechert et al. explain the steps and methodology used to develop the Urbach Tower in Germany, a 14-meter-high building made of a single-curved shell structure [109] . The complex shape of this project was made of self-shaped CLT, using the natural shrinking of wood and the prefabrication technique.

The author uses an integrative design process to develop the tower, where the design, fabrication, and assembly are iterated to obtain the best result. Additionally, Jamnitzky and Deák described the process in the current development state of the Technical University of Munich (TUM) Campus in the Olympiapark in Germany [110] . This project is made of 80% wood, and the ceilings are made of CLT-concrete composite material. Part of the roof has 18.3 meters of cantilever projection. All the CLT panels were prefabricated, and even the concrete composite parts used offsite panels but in-site concrete cast. Moreover, Gasparri and Aitchison made a novel development design technique for CLT walls, including facades, with the help of a unitized timber envelope [111] . Their design allows them to prefabricate the walls, but the installation process does not need to access facades from the outside to complete joints, reducing part of the construction time.

The journals obtained under the "digitalization" inquiry are far from the concept of the digital twin, initial searching intention, and trending in the construction industry. The results are in completely separate fields where new technology is used, like finite element analysis, computer-assisted design, computer vision, and others. One example of these journals is the work of Gamerro, whose work is dedicated to the development of digitally produced wood-wood connections for free-form structures [112] . Another instance is Ahmadian Fard Fini et al., who used surveillance camerate to automatically track the installation speed in prefabricated CLT buildings [113] . However, although the work of these authors is highly valuable, they do not reach the desired research field, digital twin, or even cyber-physical systems. This only highlights the lack of work for digital twin examples in Cross-laminated timber, despite being a trend in the construction industry.

There are two types of studies found in the journals obtained in the automation section. The first studies cover mass-customization, a topic from Industry 4.0, in the design of buildings with Cross-laminated timber. Bianconi et al. used generative algorithms and evolutionary principles to develop a web-based design space catalog for timber structures [87] . His form-finding methodology aids in providing a visual representation considering the constraints and construction restrictions from the setup, helping developers to make better decisions on the final shape of the building. Similarly, Jalali Yazdi et al. used a genetic algorithm to study mass customization [114] . Yet, his approach looks for cost optimization where his work considers the production process variables and provides the design with the lowest cost. The second topic is the usage of industrial robots in the manufacturing process of CLT projects. Joyce and Pelosi researched Japanese joinery techniques for the union on CLT panels [115] . Their case study used an ABB® industrial robot because of the facility these robots have when handling complex movement. There are two other study cases, like the one from Früh et al., who worked on a hybrid shell structure of CLT and concrete for the train station in Stuttgart [116] , or the work from Gollwitzer et al., who made an abaxially curved shell for the synagogue in Regensburg[117] . Both cases had to use industrial robots because of the complex shapes of their design and for the convenience of the robots' 6 axes, which can easily handle these movements.

From the scientometric analysis and the deeper review of the trending topics, it is possible to see research gaps in the construction industry for Cross-laminated timber.

However, as explained at the beginning of the article, the intention is to find opportunity areas for CLT manufacturing in the innovative path of Industry 4.0. Therefore, it can be said that there are two possible research gaps in the findings of this study. First, there is no study for developing a digital twin for the offsite manufacturing of Cross Laminated Panels with the usage of industrial robots. The digital twin is a trending area for construction as shown in clusters from Table 2-8, but there are no articles found on any implementation for CLT; and, following the trending of automation from the deeper review, it is critical to consider industrial robots as they show an advantage when handling complex shapes. Second, once the digital twin is implemented, it is essential to automate its manufacturing process to help developers make decisions and reduce production time. Considering the work from Bianconi, automation is a critical feature for construction as it makes the industry more efficient and saves wasted time from developers. Additionally, it will make no sense to develop an advance digital twin for CLT and leave the programming manual.

2.6. Conclusion

Cross-Laminated Timber is a material that has taken attention in the last years in the construction industry, and researchers and practitioners are interested in its application. A scientometric comparison study between research for this material in construction and Industry 4.0 was proposed to understand the current status and global trends for CLT. Although the study was observed from a manufacturing perspective, the results obtained from both analyses are uncontaminated, and the manufacturing inclination can be seen only at the end of the study. Multiple literature reviews have already been attempted, yet, this paper presents the first scientometric comparison study of the field as a whole, where 753 documents, between journals and conference proceedings, were considered for Cross-laminated timber and 567 for Industry 4.0 in construction. The science mapping approach provided the key researchers and institutions, the condition of the research field, and important topics in both areas. The CLT mapping found that the authors have emphasized the structural behavior of the material, its properties, and environmental impact. This result can be seen in different sections; even the most populated journals are related to structural themes. On the other side, the mapping for Industry 4.0 in construction has given broader results, and it is possible to say that its development is still an infant. This was concluded from the clusters obtained in the co-citation network as the most populated group was "literature reviews", highlighting researchers' interest in the topic. Aside from this cluster, there is a high interest in research themes like digital twin, prefabrication, BIM, and automation. These clusters had a deeper inspection to understand the latest publication in the five years for CLT. The issue to be highlighted is the lack of research on the "digital twin" for Cross-laminated timber, even though this is an essential theme in construction. In prefabrication, or called off-site by other authors, have journals related to three areas, mechanical behavior, comparative studies, and design. On the other hand, in the automated section, it was found that most of the publications are divided into two subgroups, mass-customization and industrial robots for manufacturing.

Regardless of the contributions found in this article, the discoveries should be considered in light of some restraints. As explained before, the findings are constrained by the selected keywords and the additional restriction set as input in the inquiry of the academic data; therefore, the scope of coverage for the existing literature is limited. Moreover, interrogating the reasons, "why" and "how", of the academic journals used in this study is out of the scope of the objectives. Thus, even though research gaps have been identified, pursuing these opportunity areas will work for future research. In addition, it is essential to do a similar analysis in the near future to observe the evolution of the research field and oversee its progress.

Chapter 3. Design and simulation of an automated robotic machining cell for cross-laminated timber panels

3.1. Introduction

Cross-laminated timber (CLT) is an innovative construction material that has been arising in the last decades due to its advantages over traditional wood structures. CLT provides a novel solution to wooden structures that reduces cost and lead time on building construction. In addition, CLT panels have a low environmental footprint, which is crucial for the sector in its efforts to become more sustainable (construction provides up to 30% of the global annual greenhouse gas emissions and consumes up to 40% of the total energy [118]). From the economic side, CLT is becoming a more feasible construction material than concrete and steel [119] ; based on the increase in CLT raw demand, production, and exports since 2010. CLT demand is estimated to be above one million cubic meters in 2018, suggesting that CLT-based projects are entering into a mature state of mass production [120] . This demand increase has pushed CLT buildings even in markets where economic factors for wood construction are not ideal, with China as an example [121] . Timber boards now include bamboo as a composite material in China because of its challenges, showing the great flexibility CLT offers, not only in design but also in material selection.

Cross-laminated timber panels must go through different manufacturing processes: lumber selection, flattening, adhesive application, and others [122] . Machining and cutting are critical in these manufacturing processes because they define the panel's shape. Architects desire to design buildings with more complex shapes, such as freeform structures, and these buildings could not be developed without integral mechanical joints. This joint type is crucial for CLT panels because it allows for a degree of freedom as a self-locking system and permits for an incredibly rigid structure without excessive fasteners or reinforcements. Nonetheless, machining the new type of interlocking joints requires more acute angles; therefore, 5-axis CNC machines are needed instead of the conventional 3-axis machines [123] . However, using 5-axis machines for cross-laminated timber generates certain problems: the cutting spindle must move through a large acute space, making the extraction of dust challenging; even with the additional axes, the machines require custom-made tools to achieve the required prismatic geometries; and, the clamping system is challenging for large batches of individual shaped plates, forcing the machines to reduce the cutting velocity and quality [123] . As quality and productivity become the selling points for offsite construction practitioners, improved designs and systems are required to keep up with the demand and overcome the customer bias against prefabricated components [16], [21] .

Subsequently, introducing a robotic solution to CLT machining can overcome the challenges reported thanks to their great flexibility, adaptability, and accuracy. However, as shown in state-of-the-art, there is no development in the academic literature on robotic machining cells for full-sized cross-laminated timber panels. This is the research gap to expand in this paper. The only instances found consider sub-processes for door manufacturing or handle purely small hollow timber panels. Therefore, in this study, an automatic robotic cell for machining CLT panels is developed in a digital factory environment and simulated to validate its performance.

3.2. State-of-the-Art

The tasks robots usually perform for the wood manufacturing industry are of low accuracy; for instance, handling, varnishing, and palletization [124] ; and according to previous studies, barely 0.2% of all worldwide industrial robots are used for woodworking processes [125] . However, it is more often seen as the natural replacement of computer numerically controlled (CNC) machines. With the novel collaborative generation of robots, this trend is expected to continue, as they provide benefits like reduced product cost or increased work-cell flexibility. It is important to mention the additional degrees of freedom an industrial robot handle for its operation, especially when compared to conventional CNC machines, where increasing a degree of freedom is extremely costly [126] .

There are studies about the forces a robot handle in the process of machining wood. On one side, Ayari et al. analyzed the machining behavior of cutting tools on hardwood and medium-density fiberboard (MDF) with a KUKA® Kr 210 L 180 [124] . The authors found a cutting force of 69.94 N for beech (hardwood) and 38.7 N for MDF; with a variation of the accuracy of 0.8 % and 0.6%, respectively. On the other side, Klimchik et al. researched families of KUKA®'s models, where different features are studied as error compensation, optimal task zone, payload, cutting forces, and accuracy. The results show an accuracy of 0.57 mm while sustaining a cutting force of 2000N for the robot KUKA® KR500 [126] .

Contrary to steel and aluminum, machining wood is not as widely common, and it is considered a soft material in comparison; yet, wood is different from other components because it is grown naturally and could be of different consistencies, soft, hard, or composite wood, MDF as an example, and most of the knowledge in the woodworking sections comes from skilled craftsmen. Different authors have studied parameters as feed rate, spindle speed, and stepdown because an incorrect configuration will leave a poor-quality surface, generate chips, and cutting marks [127] . Krimpenis et al. optimized alder wood's surface quality for a musical instrument, where smooth surfaces and low roughness are critical [128] . The authors used genetic algorithms for this application; thus, a feed rate of 669 mm/min, a stepdown of 5.8 mm, and a spindle speed of 24,000 rpm gives the best surface quality [128]. Diversely, other researchers have taken a stochastic approach with the usage of the design of experiments to optimize machining parameters. Hazir et al. and Koc et al. ran studies with wood present in the furniture industry (MDF, beech wood, and ayous wood) [125], [126] . They obtained the following parameters as best from this analysis: feed rate of 2 m/min, spindle speed of 18,000 rpm, and stepdown of 2 mm.

Different efforts of automated machining robots for woodworking processes can be found in the literature, mostly covering off-site construction and pre-fabrication [129]–[131] . Nicolescu et al. presented a virtual robotic framework station for machining wood panel doors, where the main emphasis is to remove the material on hinges and door lock cavity [132] . This station is equipped with an ABB® IRB 2600 robot, an ABB® IRBPK300/1000 workpiece positioner, and a stand for multiple tools, where the functionality of the robotic station is validated through a simulation on Catia® DMU Kinematics.

On the other side, Wagner et al. developed an in-site flexible robotic timber construction platform (TIM) equipped with functions of assembling, gluing, nailing, and machining [133] . TIM platform is dedicated to manufacturing "cassettes", hollow timber structures with individual shapes, which are assembled like a puzzle. With this in-site robotic platform, the construction time is improved because there is no waste translating the cassettes from the manufacturing supplier, and any error can be fixed on-site. Moreover, the robotic platform has an average milling time of 15 min per operation, and it was capable of machining with a deviation of less than 0.5 mm against the ideal model, a critical feature for the assembly of the BUGA pavilion building. The cases above prove the feasibility of robotic automation on wood machining processes and the advance they can represent from a performance perspective. Nevertheless, the surface quality required in construction is not as strict as for the final finishing, meaning that rough machining can be considered for similar robotic stations. Thus, a feed rate of 150 mm/s and a maximum of 100 mm of stepdown for the point milling tool can be implemented accordingly to the guidelines [128].

The next step of the paper is to design the robotic station now that it is understood the feasibility of using robots to machine CLT panels. For this objective, the methodology STCR-TMS is used. STCR-TMS eases the implementation of robots in the construction industry and formalizes the development of the robotic cell. Some of the methodology's advantages are the issues included, like considering the know-how of stakeholders, best practices in the industry, simplicity, high scalability, and looking for a cost-effective approach to the design [134].

3.3. Robotic Cell Design Methodology

This study focuses on developing a virtual automated robotic machining cell for cross-laminated timber panels with the methodology STCR-TMS (single-task construction robots – technology management system) [134] . Figure 3-1 shows an overview of this methodology's layers and phases, where the first three layers belong to engineering and management systems, and the last layer are stand-alone elements. Similar to the Deming Cycle, STCR-TMS consists of iterative design cycles with four layers and four main design phases: requirement engineering, development sequence, implementation and prototyping, and performance evaluation. The development of the robotic cell in this article covers only the first layer. Some elements such as manufacturing, integration with current infrastructure, business model, and economic performance are not included at the moment due to physical and time limitations but will be pursued in the future.

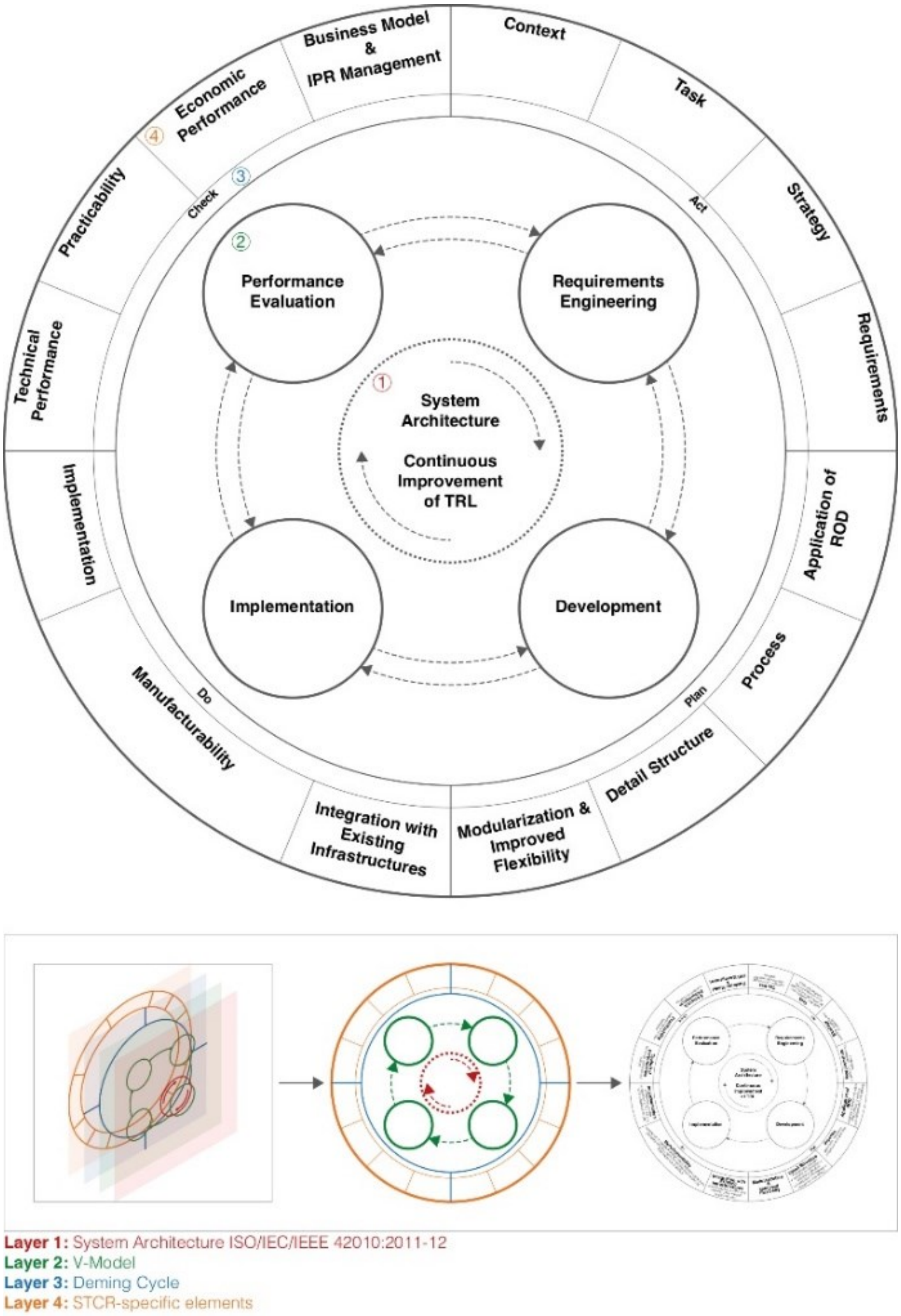


Figure 3-1. Visual representation of STCR-TMS methodology. Picture used with the granted permission of the authors [134].

3.3.1. Requirements engineering

3.3.1.1. Context

As stated in the literature review, robotic applications for machining of cross-laminated timber panels have an incredible potential to increase productivity, quality, and flexibility to the industry. For these reasons, a robotic cell is targeted to be designed in this paper.

3.3.1.2. Task

The robots are tasked to remove the necessary material to shape the stock-sized CLT panel as designed. Different tools, like saws and rough end mills, are used due to different geometrical shapes for windows or doors and additional features proper to CLT building techniques.

3.3.1.3. Strategy and Requirements

From a business perspective point, the system must be able to cover a wide array of dimensions of CLT panels. As mass customization becomes a must in the offsite construction industry, this flexibility of design is hence required.

The automated robotic cell must cover two main requirements: 1) support the required cutting forces (minimum of 2000 N [126]); 2) adjust to the CLT panels characteristics listed below:

- Height: 2.5 - 3 meters
- Thickness: 0.25 - 0.5 meters
- Length: 10 – 18 meters
- Density: 500 kg/m^3

3.3.2. Development Sequence

3.3.2.1. Application of Robotic-Oriented Design

Given the aforementioned requirements, the industrial robot ABB® IRB 7600 is selected (see Table 3-1). Furthermore, the maximum specified dimensions for the CLT panels in the designed machining cell require lengths up to 18 meters, which is impossible for a stand-alone robot. Subsequently, the use of a track system to displace the robots along the work piece is necessary. For this, the track motion ABB® IRBT 7004 (see Table 3-1) is used due to its travel length of up to 19.7 meters.

Table 3-1. Technical parameters for the ABB® IRB 7600 & IRBT 7004.

ABB® IRB 7600		ABB® IRBT 7004
Payload: 500 Kg	Axis 1: ± 180°	Length: 1.7 - 19.7 m
Number of axis: 6	Axis 2: + 85° / - 60°	Pos. time: 1.7 sec @1 m / 5 sec @5 m
Repeatability: ± 0.3 mm	Axis 3: + 60 / - 180°	Acceleration: 1.8 m/s2
Ctrl.: IRC5 Single Cabinet	Axis 4: ± 300°	Speed: 1.2 m/s
Weight: 2400 Kg	Axis 5: ± 100°	
	Axis 6: ± 360°	

Now, CLT panels have a high density, and according to the requirements, the working part can weigh up to 13.5 tons. Such weight makes it unthinkable to handle for an industrial robot. As such, an independent system to handle and clamp the working part is necessary. Therefore, the robots handle only the machining operations while shifting the responsibility to carry the load and perform the required forces to clamp the work piece to this independent system.

3.3.2.2. Processes

The loading and unloading of the work piece to the designed robotic cell is not included in the scope of this article. It is assumed that conventional cranes can handle this part of the process. Then, once the system is loaded with a stock length CLT panel, the independent system positions itself into an initial state and clamps the panel. With the working piece fixed, the robots take the tool required and start the machining process, and it is considered that only half of the depth from the top view is poscessed and the rest will be finished once the panel is flipped to the other side. The cutting patterns to be followed are pre-set based on the final panel design. The cutting process starts from the inside out and from left to right. Only once the robot finishes all the scheduled machining with the current tool does it change to the next one. This iterative routine continues with the machining process until it completes all the cutting layouts. It is important to mention that the independent system needs to be able to move in order to allow access to all areas of the panel during operations. The desirable outcome is to avoid any interference and have the flexibility for all kinds of panel designs and cutting layouts. A virtual representation of the tools can be seen in Figure 3-2.

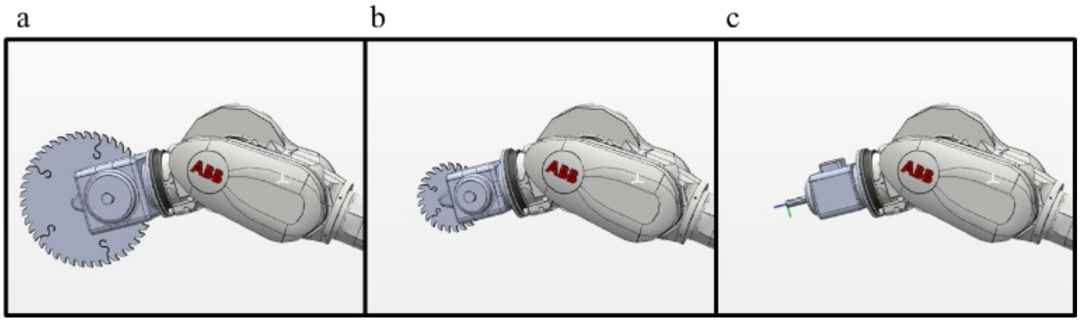


Figure 3-2. Tools design representation in RobotStudio®: (a) circular saw of 500 mm of diameter; (b) circular saw of 10 inches of diameter; and (c) rough end mill of 25 mm of diameter.

3.3.2.3. Detail Structure

The robotic cell then consists of two robot arms mounted on the track motion rails, as well as the independent system. All the components in the machining cell are placed directly on the floor to minimize installation costs. The CLT panel is then placed in a horizontal position, supported by the independent system (hereafter referred to as the flexible clamping system), which is mounted and anchored to the floor. This system levels up the panel to an appropriate height that eases robot pathing. This flexible clamping system is able to move along and across the working piece. These degrees of freedom are critical due to the high variation in the panel layouts and will allow the robots to have access to all the machining features without interference concerns. The flexible clamping system, shown in Figure 3-3, is a concept developed for this specific study, and the components considered are listed here:

a) Steel plate of half-inch thick as the initial base;

b) Wide ball-bearing carriages and rail (6382k910) with a load capacity of 14,000 lbs. each;

c) Servomotor with RMS torque of 8.1 N-m, peak torque of 32.9 N-m, and a maximum speed of 2760 rpm (CPM-MCVC-D1003P-RLN);

d) Worm gear;

e) Industrial polymer rolls of 4 inches;

f) Industrial pneumatic cylinder with a stroke of 200 mm and max. operation pressure of 1.0 MPa (SMC HYG50TFR-200).

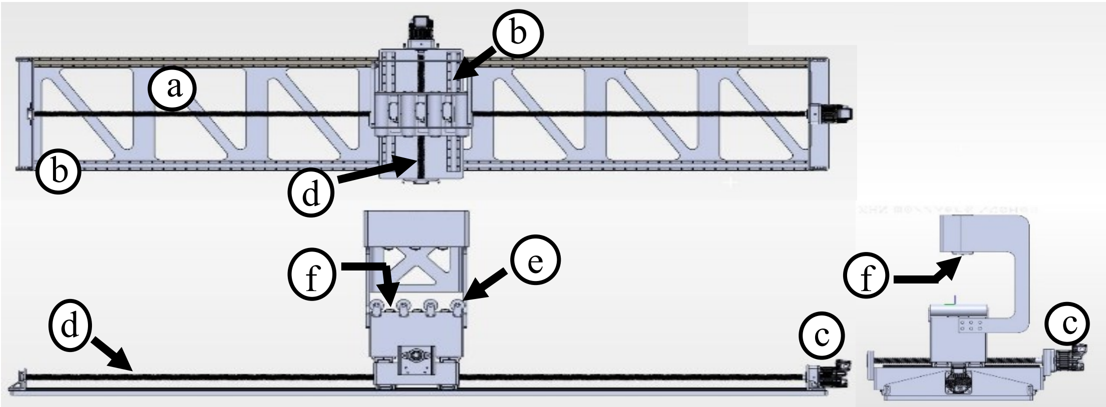


Figure 3-3. Flexible clamping station: (a) Steel plate; (b) Wide ball bearing carriage and rail; (c) Servomotor CPM-MCVC-D1003P-RLN; (d) Worm gear; (e) Industrial polymer rolls; (f) Pneumatic cylinder SMC HYG50TFR-200.

This clamping system is designed with a stochastic methodology from the industry, see Figure 3-4, where the first step is to consider the design requirements and limitations. From this step, a "C" shape is selected to clamp the working piece due to its prismatic pattern.

Additionally, industrial polymer rolls are considered in the panel's bottom contact to keep a degree of freedom, and six pneumatic cylinders are incorporated as the holding mechanisms. Then, checking the system's functionality, it is decided to split the mechanism into two sections to control the position in both axis, "X" and "Y." Similar to CNC machines, it is thought to control the displacement of the clamping system with servomotors and worm gears. Four linear bearing carriages and rails with a load capacity of 14,000 lbs. each are included per axis.

Moreover, considering the design's cost impact, it is decided to limit the system to 6 meters in length, helping in the next phase's modularization. This flexible clamping system levels up the panel to an appropriate height that eases robot pathing and allows both robots to move along and across the working piece. The degrees of freedom are critical due to the high variation on the panel layouts. They will allow the robots to have access to all the machining features without interference concerns.

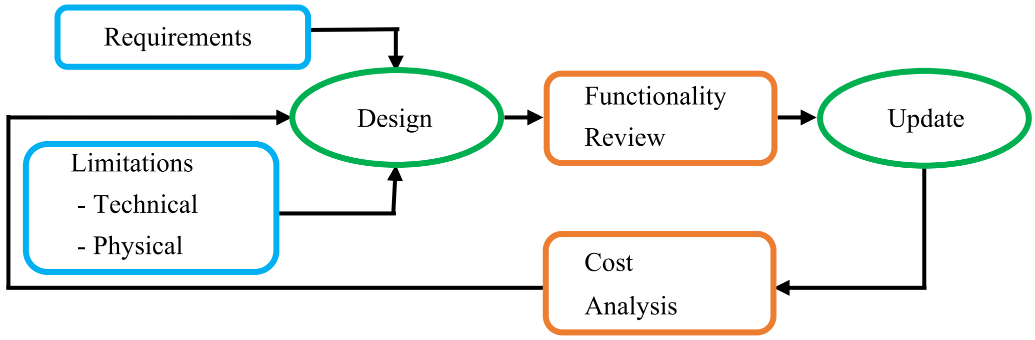


Figure 3-4. Stochastic Design Methodology by the authors.

3.3.3. Modularization and Flexibilization

The entire automated robotic machining cell is designed with modularization and flexibilization in mind. An overview of the proposed robotic cell is shown in Figure 3-5. The robots are placed side to side on top of the track motion system enabling them to reach all the areas of the work piece. This setup allows the robots to a machine in parallel, reducing the production time. Three flexible clamping systems are placed per side, each with a travel distance of six meters along the working piece, and separated half a meter from across each other. These features in the clamping system will make the entire station flexible enough to cover the variations in the cutting layouts. Finally, each robot has a tool stand next to the start of its rail, giving quick and easy access to all the tools required without interfering with the clamping system.

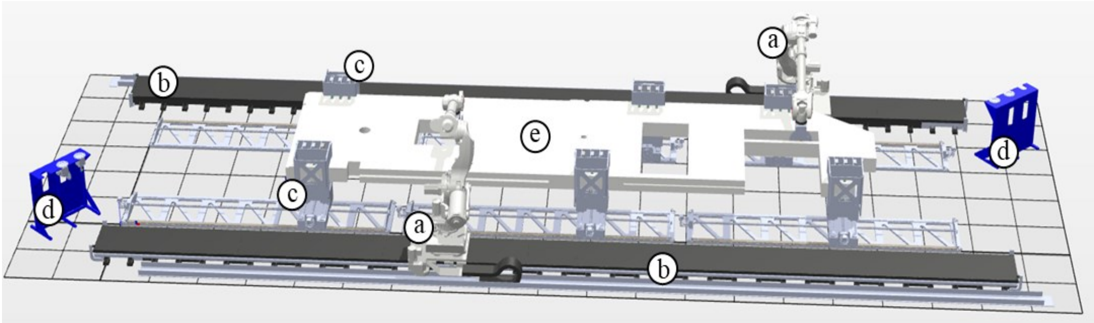


Figure 3-5. Automated robotic machining cell for cross-laminated timber panels: (a) Robot ABB® IRB 7600; (b) Track motion ABB® IRBT 7004; (c) Flexible clamping System; (d) Tool stand; (e) Minimum viable product.

3.3.4. Implementation and Prototyping

The circular saws, the end mill tool, tool stands, and the flexible clamping modules are initially designed in the computer-aided design software SolidWorks® 2019. Once finalized, they are imported into the simulation software ABB® RobotStudio 2020, where the industrial robots and track motion systems are already included in the ABB® library. This simulation software is chosen because it includes real representative data from each of their industrial robots, and the simulations run within this software end with realistic performance using the same controllers that would be used in the industrial setup. The robotic station is kept only as a digital factory due to physical limitations.

3.3.5. Performance evaluation – Proof of Concept

To evaluate the feasibility of the proposed design, a simulation of the machining process for a CLT panel is implemented in RobotStudio®. This approach also enables the analysis of the performance of robotic machining cells for CLT panels. A CLT panel is designed to include all features found in most CLT panels, such as windows, doors, column anchors, and internal splines, among others. Such a panel is considered the minimum viable product for the robotic cell. Figure 3-6 shows the manufacturing drawing with the cutting pattern for this panel. The simulation results and performance metrics obtained are presented and discussed in the following section.

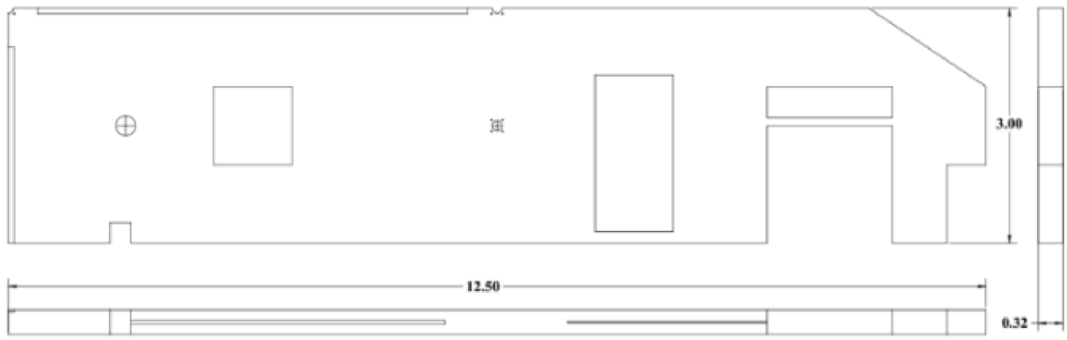


Figure 3-6. Minimum viable product for CLT panels.

3.4. Results and Discussion

The proposed robotic machining cell for CLT panel timbers is fully simulated in RobotStudio®. The resulting cycle time of the station required to finish the panel, shown in Figure 3-6, is 18 minutes and 20 seconds. This includes the time required to change tools and for the flexible clamping system displacements. Taking into consideration the overall dimensions of the CLT panel, it can be estimated that the production rate for this robotic machining cell is about 22 sq. ft/min.

Additionally, a lean mapping was done to the robotic cell where value-added and non-value-added activities are discussed to showcase the efficiency of the design proposed. The value-added ones would be the actual time the robots are performing machining operations on the panel, while non-value-added activities are any other tasks during the process, like free positioning of the robots or changing tools. Analyzing the simulation results, the proposed station has an efficiency of 83.3% from a LEAN perspective. An overview of the lean analysis of the performance of the station is shown in Figure 3-7.

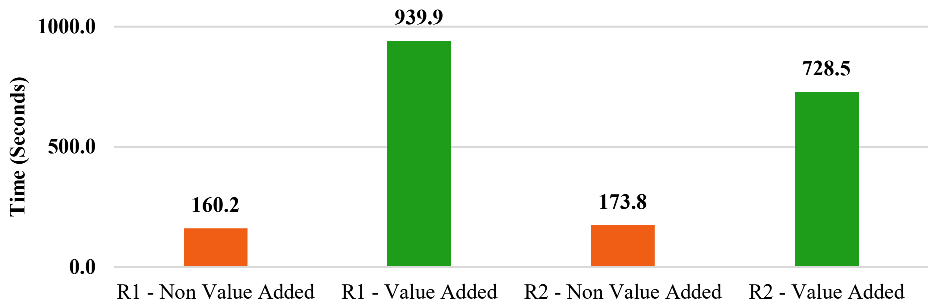


Figure 3-7. Lean analysis over the robotic cell operations.

Another metric to be considered showcasing the performance and behavior of the robotic cell is the total utilization of the tools. This is especially important to understand the maintenance needs of such a system. Based on the usage of each tool during the entirety of the machining process, the utilization graph is shown in Figure 3-8. It can be observed that the milling tools are the most used as milling covers more than 81.9% of the time in each robot. This might be explained due to the large number of construction features required on CLT panels in column anchors and splines.

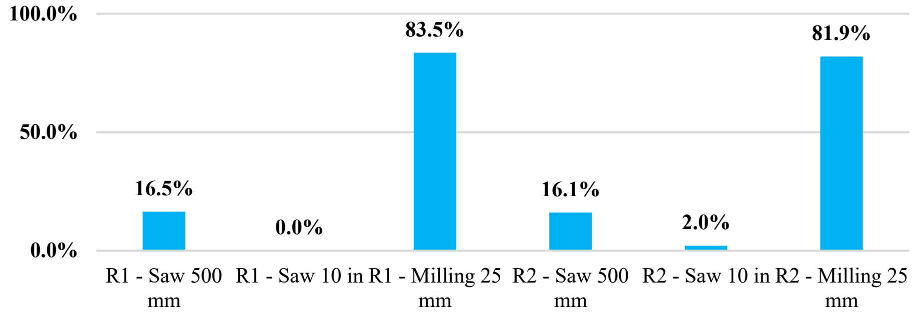


Figure 3-8. Tool utilization per machining operation

As future work, the physical validation of the automated robotic cell would be pursued. Following the virtual design proposed, a real prototype will be set up. Actual tolerances, the tool changer adapter, tool calibration, the tools' performance, surface finishing, dust collection, and other features are missing and can only be done with a physical system. In addition, the flexible clamping station needs physical validation as there are parameters to improve in case it is necessary like vibration while machining.

CLT manufacturing is highly variable, and finding the machining recipe and the limits for machining parameters is essential in the construction industry. For these reasons, implementing a pilot would be highly recommended before considering this work as a final production process, and if it is possible, an iterative process to find the optimal robotic station will be ideal.

3.5. Conclusions

Following the great capabilities of robotic cells for wood machining, this study proposes a fully automated robotic cell for the machining of CLT panels. Following the STCR-TMS methodology for the design of single robotic cells, a flexible and competitive solution is presented. The design is then simulated for validation purposes with a complex CLT panel that contains all the possible features that can be encountered during CLT machining processes. With the simulation in place, it was found that the robotic machining cell has a cycle time of 18 minutes and 20 seconds, a production rate of 22.02 sq. ft/min, an efficiency of over 83.3% from a lean perspective, and high utilization of the end mill tool, over 81.9%.

Chapter 4. Automatic target-path planning generation for robotic CLT machining station

4.1. Introduction

The most traditional construction method in North America consists of wood frames, where all the timbers are gathered and assembled on-site. This process, however, is prone to error thanks to a vast enrolment of the human factor, is prone to variability and delays, in case of a day of rain or snow, and the time consumed for a single build is unjustifiable [16]Click or tap here to enter text.. A proven way to enhance productivity in construction is with offsite methods, a technique that requires the fabrication of partial wood frames in a dedicated facility, in which only the final assembly is made at the construction site, significantly increasing the quality and productivity of the construction. As a novel alternative to traditional structural elements, mass timber construction (MTC), which refers to different types of massive wood planar or frame elements for walls, floors, roofs, and other critical pieces of the building, has become popular lately [1]. MTC not only has the advantage of offsite construction, but it has greatly appreciated properties such as lower carbon footprints, lighter weight, and reduced total cost when compared to traditional concrete or steel buildings [119], [135] . Mass timber construction has multiple options for material bases like glue-laminated timber (GLT), structural composite lumber (SCL), or cross-laminated timber (CLT). CLT is the most commonly used material for floors or walls. CLT boards are made of various layers of solid lumber, with the grains alternating between each layer and using an adhesive to bond the entire panel. This material, even being lightweight, has a great strength to sustain high vertical load, and its performance is excellent against seismic, fire, thermal, and acoustic [136]–[138] . Additionally, CLT has great versatility because it is not exclusive to wall applications as it can cover roofs and floors and be used in conjunction with other materials like steel and concrete for additional support. Even though wood frames and CLT panels are used for offsite construction, their fabrication process is completely opposite from each other. On one side, one needs to add and assemble multiple timbers to reach the shape of a partial frame, which is considered empty and will require insulation later on in the process. Conversely, a CLT board is solid, and the material must be removed by machining to reach the required shape by the construction design.

The properties of cross laminated timber allow architects and developers to push for more challenging buildings, like the Oakwood Tower, which is considered one of the first super tall buildings made of CLT with an outstanding height of more than 300 meters [102]; or like the BUGA wood pavilion with a complex biomimetic shape that was achieved using advanced automation and robotic systems [139], [140]. The key feature in these designs is the division of the entire build into multiple interconnected pieces, where each of them is a CLT board required to be manufactured, and each CLT board is saved in a bill or list of panels. Once this bill of panels is ready, each panel's blueprint is sent to the manufacturer, which handles the machining of each piece. Presently, developers use software to create building information modeling (BIM) models to improve managing all the stages of the construction, from design to release. This tool helps keep all the critical information in one place and prevents common design errors, such as omitting the latest modification in the building. Another benefit of this management tool is the direct link between suppliers, architects, and engineers. Currently, CLT panel manufacturers take the dimensions and desired shape of each panel and manually set up their machines for its manufacture; however, this approach is tedious, time-consuming, and relies heavily on the skills of the experts. There is currently no commercial product for the project's design phase, which could close the gap between the CLT-based building up to the manufacturing of the boards. The closest solution known to the authors is an add-on module, named "Wood Framing CLT", available for Revit®, which helps in the shape design and allows the developer to split a simple wall into multiple panels, distribute the supports, and fasten; yet, the outcome from this software keeps being blueprints or a material list for the supplier, and there is no deep processing or knowledge offered regarding the fabrication of each board. This open loop in the developing workflow of a building could lead to high cost and time delays in case any CLT panel is not manufacturable or feasible, to begin with. Then, it is critical to have feedback in the design phase about the manufacturability of the product. Developing a system that can cover the entire manufacturing phases of the CLT panels is unrealistic due to the high diversity of shapes and sizes in the boards and the variability of machines per fabricator. Therefore, this paper aims to develop a path planning method that directly determines the manufacturing (machining) of the cross-laminated timber panels from the 3D model.

4.1.1. Related Work

Machining a CLT panel is a common process in the industry; nevertheless, the academic literature only presents research areas close to the manufacturing feedback for design with Cross Laminated Timber, yet none of them match precisely. The fundamental link between designing and manufacturing a product is process planning. Multiple efforts have beeno implement computational power in this process in the last years, best known as Computer Assisted Process Planning (CAPP) [19]Click or tap here to enter text.. Thus, CAPP is the crucial tool to unite Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM). It considers the requirements of the product (including technical properties and cost limitations) and turns them into manufacturing procedures [141]Click or tap here to enter text.. One of the approaches for CAPP is feature-based, where the geometries of the part are analyzed, and the manufacturing operations are selected accordingly. This approach is common for mechanical components; however, construction-related products face limitations when processed in this way. Still, the ease of offsite construction with CLT allows interpreting individual panels as mechanical parts to obtain the machining instruction thanks to the shape of the panels, where most of the geometries could be considered primitive prisms [16]. The authors have done an extensive literature review, and no publication was reported on Computer-Aided Process Planning in CLT manufacturing. However, the authors found Darwish's work, which conducted a study on the automation of wood-frame buildings where his systems identify the manufacturability of the buildings and generate the CNC code for machining the timbers [142]Click or tap here to enter text.. His framework developed an accurate and detailed production estimation and calculated the life usage of each part in the machine for the maintenance scheduling process.

In addition to CAPP, different fields were scrutinized to find journals related to the intention of this article, but the efforts gave scare publications; for this reason, the review in state of the art is narrowed to three closely related fields, which virtually converge in the desired research by this study. Those three areas are robotic machining, computer numerical control (CNC) path planning, and wood machining, which are addressed in the following paragraphs in this respective order.

In the field of robot machining, numerous examples of automated (or not) path planning can be found. For instance, Cui et al. developed a path planning method for an ultrasonic cutting tool [143]Click or tap here to enter text.. This ultrasonic V-shaped cutting tool is needed due to the Nomex honeycomb composite, which is used in aircraft structural parts thanks to its high specific strength, heat resistance, and lightweight. In contrast to traditional milling tools, ultrasonic gear generates a continuous chip when cutting material, removing volume chunks by chunks and making path planning a complicated task. Yet, the authors are able to automate the path planning by post-processing traditional G-code from a computer-aided manufacturing software and getting a deviation below 0.8 millimeters. On the other hand, Hähn and Weigold made an accuracy optimization with a hybrid controller compensator [144]. The authors took into consideration a path calculated by the offline software and compensated the position of the tool center point (TCP) in relation to the static and dynamic stiffness of each joint. Following the authors' methodology, the geometrical deviation of the working piece went from around 1.2 millimeters to less than 0.3 millimeters. Additionally, Lu et al. made a toolpath planning study for surface machining by optimizing the differential vector in the joints of the robot [145]. The authors achieved smooth machining of complex surfaces like those made of 3D printing, with an average roughness close to 1 micrometer. Therefore, it is possible to say that robot machining has an excellent advantage for complex paths while maintaining a good accuracy, and they can even handle non-conventional tools. Nevertheless, industrial robots are limited by the tool weight and geometry because the distribution of the load could add up excessive forces for the end-effector of the robot, making it inaccurate or even incapable of handling the machining operation. However, this study is not considering the physical limitations of the robots at the moment. Still, additional steps could be added to improve the machining performance if needed in the future.

On the other hand, path planning for CNC machines is the most developed and traditional research field, and it is common to find vast experiments and publications in the literature. Some examples of the latest developments in this field are freeform surface optimization, point cloud direct path planning, twin-tool machining, cutting force fluctuation algorithms, or time-optimal algorithms [146]–[148] . For instance, Dhanda developed a tool path planning strategy for freeform surface machining for reverse engineering purposes [149] . The author's strategy allows the generation of a CNC program from a massive point cloud without any type of CAD reconstruction, and it even allows the user to select its preference between productivity (reduced machining time) and part quality (better surface finish). Song et al. developed a highly efficient path planning method for turbine blades with the use of twin tools [150]Click or tap here to enter text.. Machining turbine blades is complex because there are different challenges to overcome, like the clamping force deformation, the thin-walled structure deformation, and residual stress. In this process, each tool is assigned oppositely to machine the dorsal and basin surface of the blade while simultaneously moving along the length of the blade, leaving a system with nine axes. The authors get the path by first calculating the iso-scallop method, and then they are equally parameterized with the least-square algorithm on each side. The machining efficiency of this method improved by 45% when compared to the traditional single-tool milling technique. Additionally, other authors developed their path planning algorithm depending on the parameters of the CNC machine; like Wulle et al., who developed a time-optimal algorithm using variability of the tool orientation [151]Click or tap here to enter text.; or Ma et al. who made its path planning method using the cutting force fluctuation for curved surfaces for better quality parts [152].

Wood machining is a research area with less attention than the most common metal machining. Wood can be found in different forms as natural wood (e.g., oak, beech, etc.) or combined with other materials like medium-density fiber boards (MDF) or high-pressure laminates (HPL); and this variation creates a high volume of dust and chips, forcing the machining system to be enclosed [153]. There are authors looking into different techniques of machining path planning because of these multiple alternatives of fibers from wood. For instance, Petrovic et al. made a tool path planning optimization for CNC machines [154]. The author takes into consideration multiple parameters such as depth cut, engagement angle, feed rate, and cutting speed to achieve minimum cutting force, maximum dynamic stability, and minimum tool wear. Another example is Makris' work on path planning optimization for the machining surface finish of pine wood [155]. The author compared four different types of path techniques, pencil, scallop, parallel, and radial, and contemplated similar machining parameters to understand the optimal process result. With a set of experiments, the obtained surface roughness is analyzed, concluding that radial and pencil techniques have a better performance on complex surfaces, while scallop is the best option for flat areas. Additionally, there are various research studies to understand all types of properties and behaviors of wood machining. Some of the areas of interest are surface quality [156]–[158] , path accuracy [159], and even an autonomous identification of wood properties during the machining process with acoustic emissions [160].

In summary, the research fields presented (robot machining, CNC path planning, and wood machining) have numerous publications for path planning applications; yet, there is a research gap in the automated path planning generation for CLT machining with features like path planning in 3D for CLT panels and not only closed to dual dimensions or 2D; a live system used as a bridge to connect design and manufacturing directly; a methodology that covers the tool selection and considers its limitations for the machining station; and, the integration of industrial robots due to its flexibility on tools and reaching capability for acute angles. In order to cover the features mentioned above, therefore, this article will present a novel method for target-path planning generation for a robotic machining station dedicated to cross-laminated timber panels.

4.2. System Framework

The system presented in this paper can be used for any general machining system as long as it uses TCP targets for its paths. A target or target point is considered as the absolute cartesian coordinates in (x, y, z) axes of a specific point relative to the coordinate system of a specific environment, see Figure 4-1. These targets or points of interest must be selected considering the constrains of the environment and the tools to be used. The suggested framework is shown in Figure 4-2, and it is composed of four components; i) STL file input for desired CLT panel; ii) constraints for the tools and robotic station; iii) proposed method process to identify the machining cuts; and iv) results and targets for the robotic station. The framework of this study is developed with Python programing language because of its ease of use, versatility, existing infrastructure, and the vast libraries it has access to.

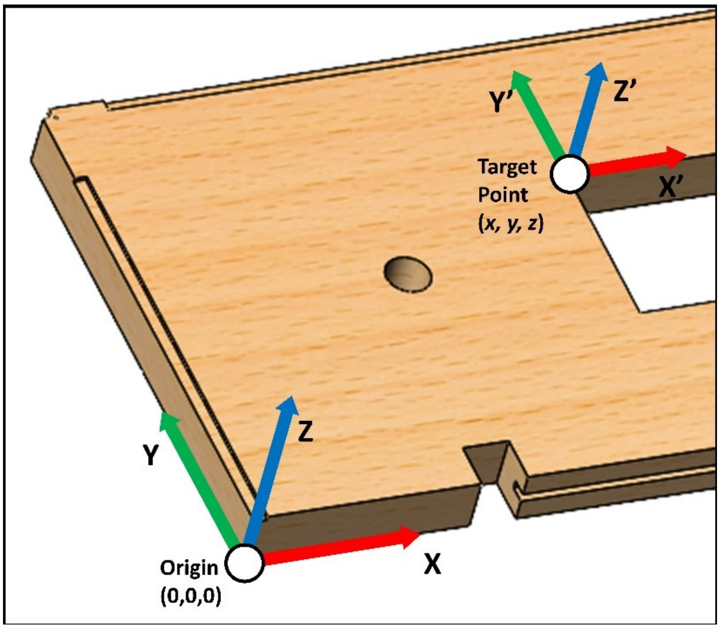


Figure 4-1. Example of target point for the coordinate system.

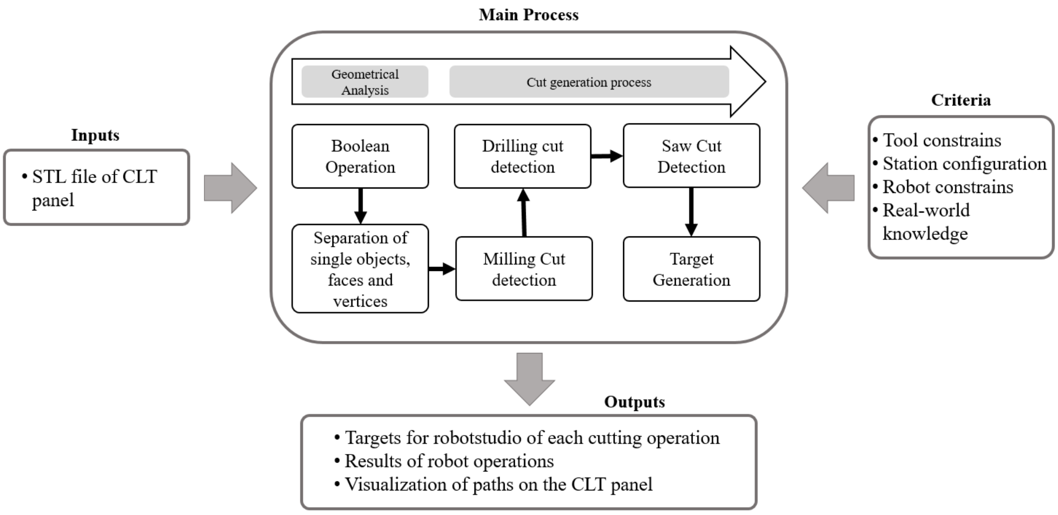


Figure 4-2. System framework overview.

Every machining station can vary in its setup, but all have similar constraints. In this case, the targets are limited to the working environment of the machining station, which could cover CLT panels with a possible variance of 2.5 meters to 3 meters in height, and from 10 meters up to 18 meters in length. As shown in Figure 4-22, it is considered that most of the machining operations are done from the top surface of the panel; and just milling features are contemplated on the bottom and top side of the board. The current method is designed for four different tools, but that could be expanded easily depending on specific requirements. The tools used in this study are shown in Figure 4-33 and they consist of a drill bit, an end mill bit, a circular saw of 10 inches in diameter, and another circular saw of 500 millimeters in diameter; these tools were selected empirically because of their high usage in the industry. It is essential to identify the tool center point (TCP) for each tool, defined as the location on the end effector or tool of a robot manipulator whose position defines the coordinates of the controlled object [161]. The TCP allows the robot's controller to change the coordinate system from the end of the arm to the end of the tool, and this ease the track of the path. The position of the TCP depends on the type of the tool, and to translate the coordinate points into the robot arm, a simple transformation matrix can be used; yet most robotic software, like RobotStudio®, already include the understanding of TCP, and they only require the relative location in the tool to the arm. For instance, the drilling bit has its TCP on the end of the piece, and it is limited up to 90 millimeters in depth. On the other hand, the circular saw of 500 millimeters has its TCP closer to the center of the disk, but it considers a safety gap to avoid any interference with mechanical gear.

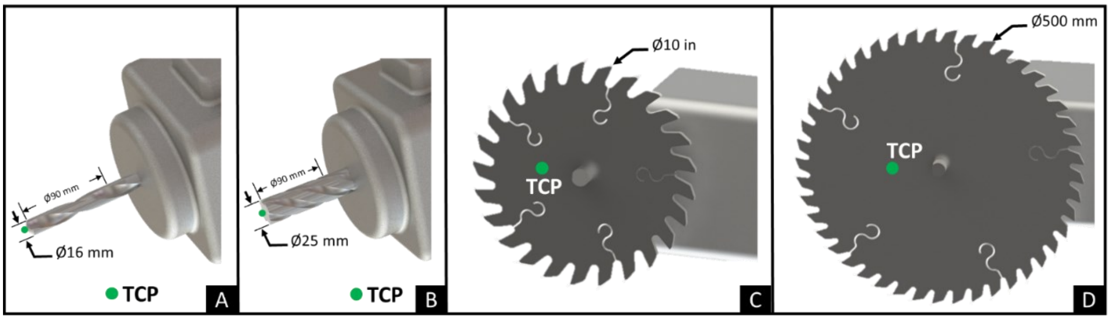


Figure 4-3. Tools considered in the algorithm. A) drill bit of 16 mm of diameter, B) end mill with 25 millimeters of diameter, C) circular saw with 10 inches of diameter, and D) circular saw with 500 millimeters of diameter.

4.3. Target-path planning method (TPPM)

The method for detecting the machining cuts of the CLT panel is presented in Figure 4-4**Error! Reference source not found.**. The diagram presents an overview of the entire process for defining the target path of each cut. Each method sub-modules are reported below, where every step is clearly explained, and details on the logic are defined. Overall, the method is split into 30 connected modules, as described in Figure 4-4. As a note, the modularization of the method was for a easy implementation of future features, like optimization or machining type; however, the integration of these modules are not considerend in the current scope. First, the solid extracted from the BIM model is split into a mesh of geometrical features. Then, those features require to be automatically recognized as basic geometrical shapes (circles, squares, etc.) by the method and tested against the tool characteristics, i.e., tool depth, straight lines, or cutting lines length. Finally, a path is calculated based on the selected tool and the identified geometry to be machined. Each element of the proposed method is explicitly described and modeled in the following subsections.

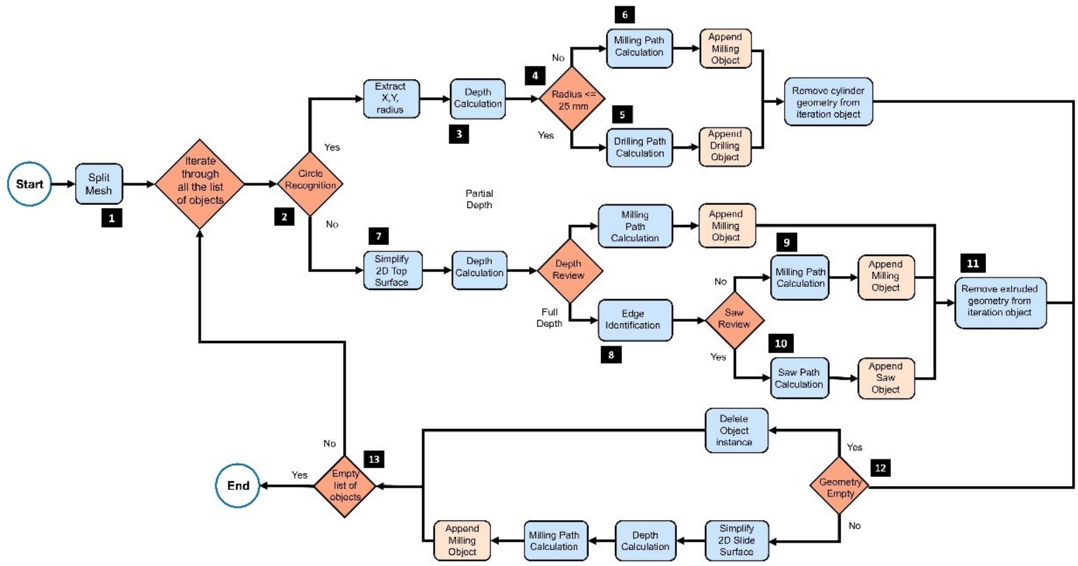


Figure 4-4. Overall algorithm for the target extraction of the cutting operations for the CLT panel.

4.3.1. Split Initial Mesh

The proposed method processes 3-dimensional models to generate targets in the virtual station. The standard triangle language (STL) file format is selected as it is well studied by plenty of authors, is uncomplicated to use, and avoids dealing with proprietary APIs of some CAD software (such as SolidWorks®). In the STL format, a 3D model is divided into multiple triangles (facets) with vertices or points that form the desired body; see Figure 4-5 for a clearer picture. A pattern of these triangular facets can represent any surface from a 3D model. Unfortunately, when processing STL files, some simple lines or primitive geometries end with unnecessary additional data, but later on, the method will explain a simplification process.

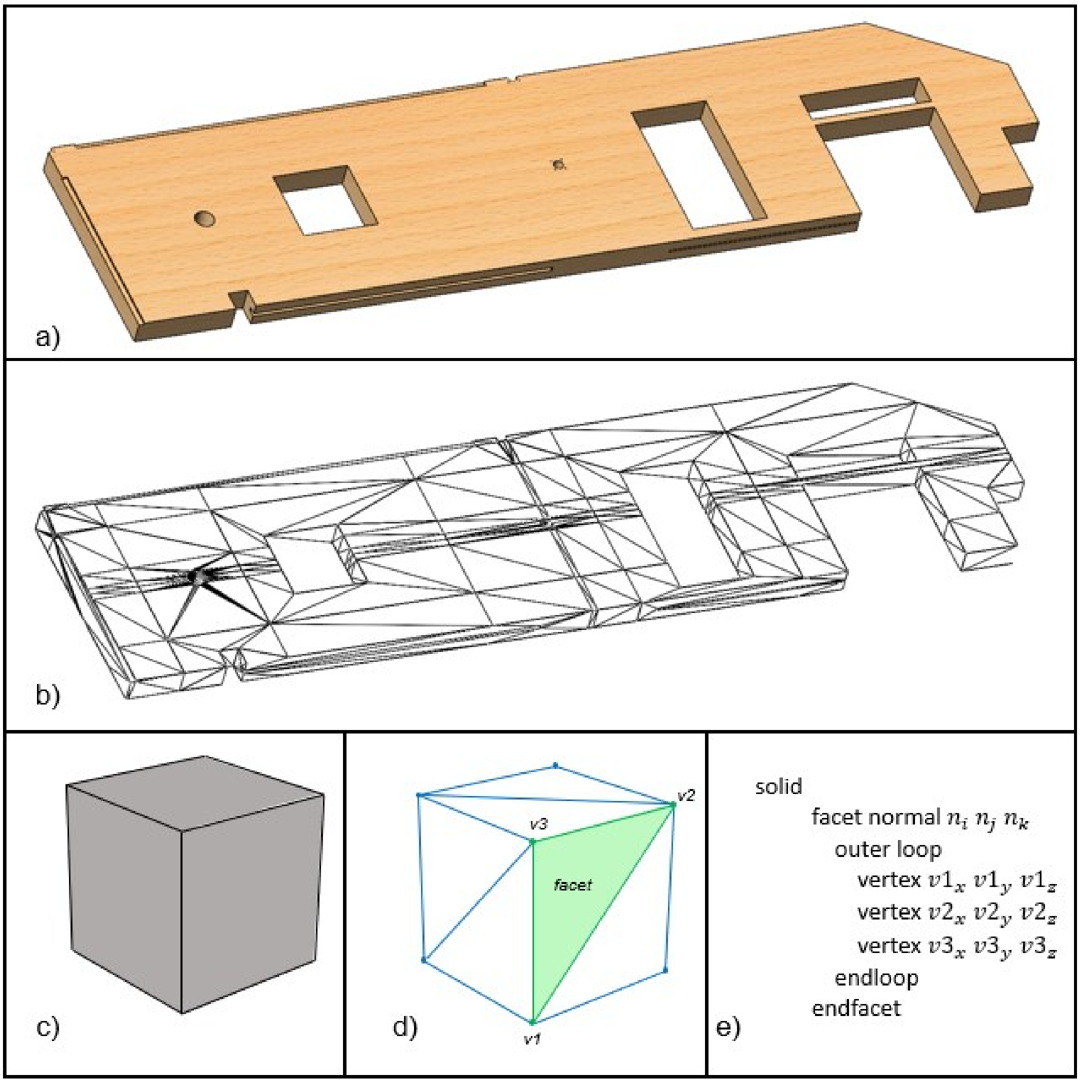


Figure 4-5. Standard Triangle Language "STL" format visualization. a) 3D model representation of CLT panel on BIM/CAD format, b) STL representation of the same CLT panel, c) Common 3D model of a cube seen on BIM/CAD format, d) STL model of the same cube showing the vertices of one triangle and its facet, e) format structure for the ASCII STL showing the framework of the vertices and facet.

In BIM, for instance, an entire building can be designed where each entity has multiple properties, like material, quantity, and mathematical model. Each panel from this can contain a 3D model representation, shown in Figure 4-5-a, and it can be exported as an individual STL file, as shown in Figure 4-5-b. After the BIM model geometry is exported in STL file format, the first process of the method is a boolean operation between the desired design and the raw material. This step is used to identify the areas of the panel, mostly solid bodies, which are the actual material to remove during the machining process. An overview of this operation is presented on Figure 4-6, where A) shows the desired design of the panel, B) shows the raw material of the CLT timber without any cuts, and C) shows the overlapping of the desired design with the raw material while highlighting the residual volume, and D) presents the set of bodies to analyze. In other words, by defining the raw material as R, and the desired panel as D, the set of individual bodies is obtained from the boolean operation in equation (1). The operation is better expressed as follows:

$$R - D = [B_1,\ B_2,\ B_3 \dots B_n]^T \tag{1}$$

$$B_i = [F_1, F_2, F_3, \dots, F_n]^T,\ i = 1, 2, 3 \dots n \tag{2}$$

$$F_j = [E_1, E_2, E_3]^T,\ j = 1, 2, 3 \dots m \tag{3}$$

$$E_k = (P_{i1}, P_{i2}),\ k = 1, 2, 3, \dots p \tag{4}$$

$$P_{ij} = (x, y, z),\ j = 1, 2, 3, \dots q\ , x, y, z\ \in \mathbb{R} \tag{5}$$

where (B_i) is the i^{th} body resulting from the boolean operation, (F_j) is the j^{th} facet that forms the i^{th} body, (E_k) is the k^{th} edge from the facet k, (P_{ij}) is the ij^{th} point or vertex to form the edge k and $\left(x_{ij}, y_{ij}, z_{ij}\right)$ are its 3-dimensional coordinates. It is important to mention that in this operation, no facet is shared among the bodies because they are completely independent objects, but within the facets, one edge can be shared between two facets, and one vertex can be present in multiple facets or edges. Once the objects are separated from the original model, each of them is analyzed to define which machining tool, robot, and target needs.

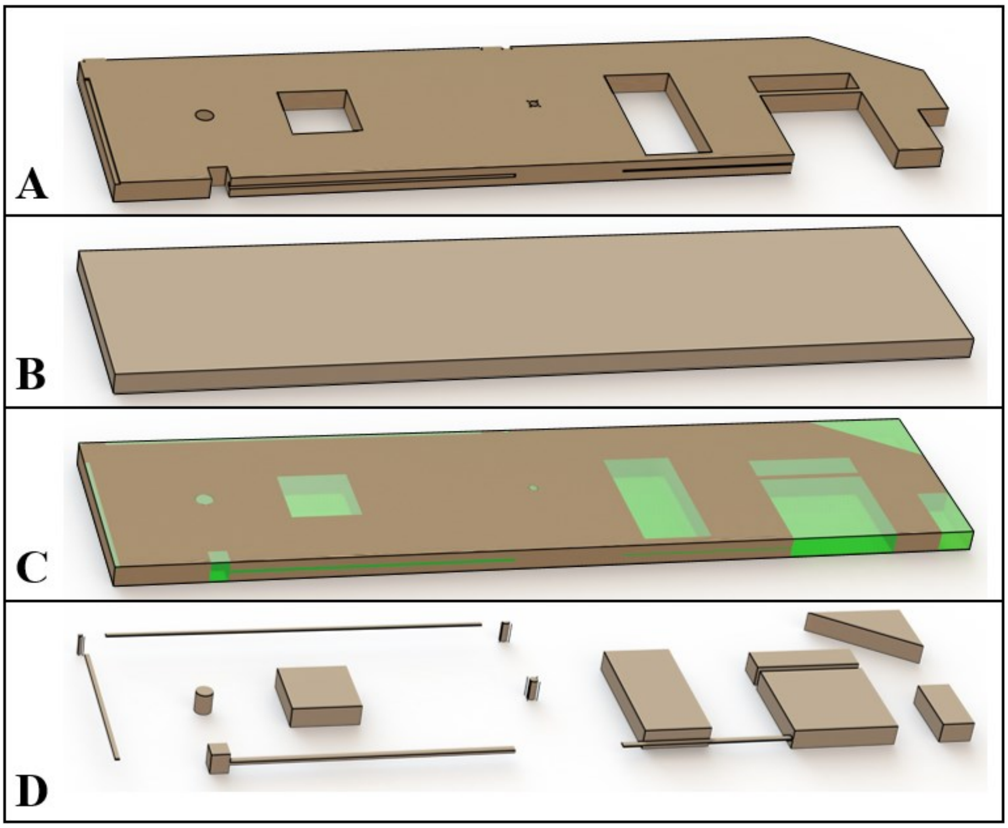
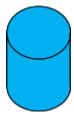
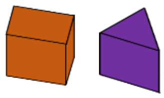
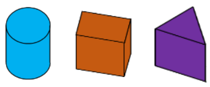


Figure 4-6. Boolean operation of the processed panel. a) original design, b) raw material required, c) overlapped model of raw material and desired design with the remaining material highlighted in green, d) bodies obtained from the boolean operation.

The next step in the algorithm is to iterate through the individual bodies and identify the main geometrical feature of each individual body. In Table 4-1, the geometrical relation with the cutting operation is shown. These geometrical relations are pertinent to the performance and physical constraints of the tools. For instance, there are prisms with a rectangular shape as the main feature with an edge length above 200 millimeters where the milling tool can take care of the cutting operation; however, the circular saws are selected because it reduces the time for the cutting operation. Additionally, the depth of the prims is a restriction because if the body does not have enough volume, the milling tool would be the only instrument capable of cutting the geometry.

Table 4-1. Geometries related to the cutting operation.

Cutting Operation	Geometries of Interest	Visual Aid	Description
Drilling	Circles		Circles with diameter of 16 millimeters
Sawing	Squares, Rectangles or Triangles		Prism geometries where the edges are longer than 200 millimeters
Milling	Circles, Squares, Rectangles or Triangles		Circles with diameter above 16 millimeters and prisms geometries with edges below 200 millimeters

Thus, the top surface is reviewed as the main geometry to define the instructions. For this reason, the boundaries of the top surface of all the bodies need to be found. All the points of the body, in turn, are checked to find those with the (z) coordinate on the top of the geometry in the z axis, and all the points matching this requirement are saved in a list of vertices named (V_{top}) as in (6), where $(z_{top\ limit})$ is the mayor value found in the z axis. In this step, the library "trimesh" comes handy as it has the function "facets_boundary," which provides a list of the list with the edges that represent the boundary of the facets in the same plane. These boundaries are compared then to find which list has all its vertices (V_{top}), defining the top surface.

$$V_{top} = [P_1, P_2, P_3, \dots, P_n]^T, \ \forall \ \{P(z) = z_{top\ limit}\} \tag{6}$$

$$B_{top} = \{[E_1, E_2, E_3, \dots, E_n]^T, \ | \ E_k \in V_{top}\} \tag{7}$$

This top surface is defined as (B_{top}), which is an array of edges (7) that has to be scrutinized to find if the body is prismatic or cylindrical. A prismatic body has rectangular or triangular geometries, as shown in Figure 4-7-A, while "cylindrical" or polygons with a close shape to a circle have a boundary with a higher number of points, as seen in Figure 4-7-B. Three conditions define if the resulting 2-dimensional polygon is a circle. First, the number of edges is counted, and those with a higher number of 4 are considered with the possibility of being a circle. Second, the angles, see Figure 4-7-C, must be obtuse and between 177 and 180 degrees. Third, the angle between two connected edges must be the same for the rest of the contour. In the case that these three conditions are true, the geometry is considered a circle.

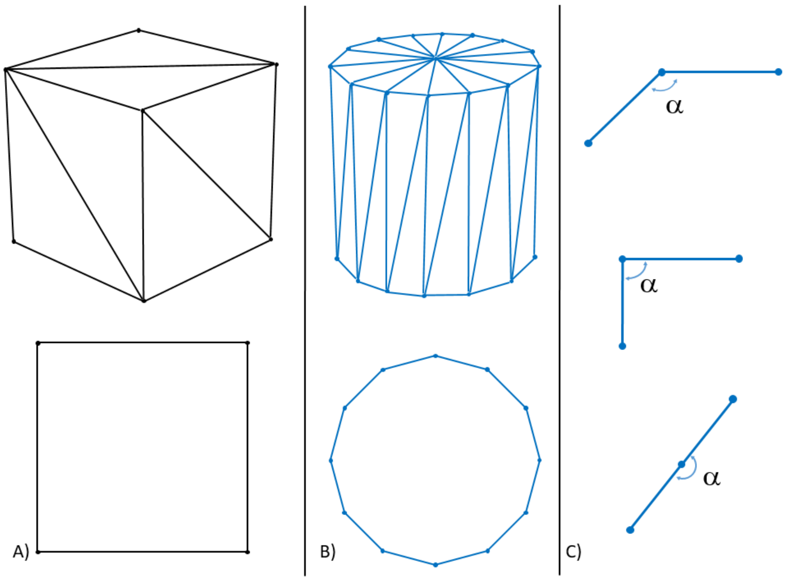


Figure 4-7. Top surface analysis of STL geometries. A) prismatic bodies representation and its top surface, B) cylindrical bodies representation and its top surface, and C) angles found in between edges of boundary (obtuse, right, or straight).

4.3.2. Circle Recognition

Therefore, one can then identify if the top surface of the polygon is circular or not, Figure 4-4-2. For circular top surfaces, three parameters must be computed: the (x, y) coordinates of the center point and its radius. For this process, the least-square circle fit method is used [162], where given a finite set of points as in (6), one wants to obtain the circle that "best" fits the points. As a note, the (z_i) value of all the points can be ignored as it is constant because all the points are on the superior surface of the body.

$$\mathbb{R}^2, \{(x_i, y_i) \mid 0 \leq \ i \ < N\} \tag{8}$$

$$\bar{x} = \frac{1}{N}\sum_i x_i \text{ and } \bar{y} = \frac{1}{N}\sum_i y_i \tag{9}$$

For an easier calculation of the center, a change of variable is implemented as in (10), (11) for $0 \leq \ i \ < N$. Once the problem is solved first in (u, v) coordinates, then they are transformed back to (x, y). Therefore, the circle will have a center (u_c, v_c) and a radius R. It is desired to minimize the equation (12) where $g(u, v)$ is used as in (13), and $\alpha = \ R^2$. In order to solve the equation, $S(\alpha, u_c, v_c)$ is differentiated, where the equations in (14) are obtained.

$$u_i = \ x_i - \ \bar{x}_i \tag{10}$$

$$v_i = \ y_i - \ \bar{y}_i \tag{11}$$

$$S = \ \sum_i \big(g(u_i, v_i)\big)^2 \tag{12}$$

$$g(u, v) = \ (u - u_c)^2 + \ (v - v_c)^2 - \ \alpha \tag{13}$$

$$u_c S_{uu} \ + \ v_c S_{uv} = \frac{1}{2}(S_{uuu} + \ S_{uvv}) \text{ and } u_c S_{uv} \ + \ v_c S_{vv} = \frac{1}{2}(S_{vvv} + \ S_{vuu}) \tag{14}$$

Once both equations are solved simultaneously, they give (u_c, v_c). Then the center (x_c, y_c) of the circle in the original coordinate system is (15). Now, to find the radius of the circle, it is necessary to expand the equation (16), where equation (17) is obtained, and naturally (18). Figure 4-8 presents a visual representation of the calculated circle from a sample of data points.

$$(x_c, y_c) = (u_c, v_c) + (\bar{x}, \bar{y}) \tag{15}$$

$$\sum_i [u_i^2 - 2u_i u_c + u_c^2 + v_i^2 - 2v_i v_c + v_c^2 - \alpha] = 0 \tag{16}$$

$$\alpha = v_c^2 + v_c^2 + \frac{S_{uu} + S_{vv}}{N} \tag{17}$$

$$R = \sqrt{\alpha} \tag{18}$$

i	X	Y	u_i	v_i
0	10.29	3.07	2.92	-15.03
1	7.38	8.17	0.01	-9.93
2	5.45	15.07	-1.91	-3.03
3	5.53	22.92	-1.83	4.81
4	6.56	27.08	-0.80	8.97
5	8.98	32.34	1.61	14.23

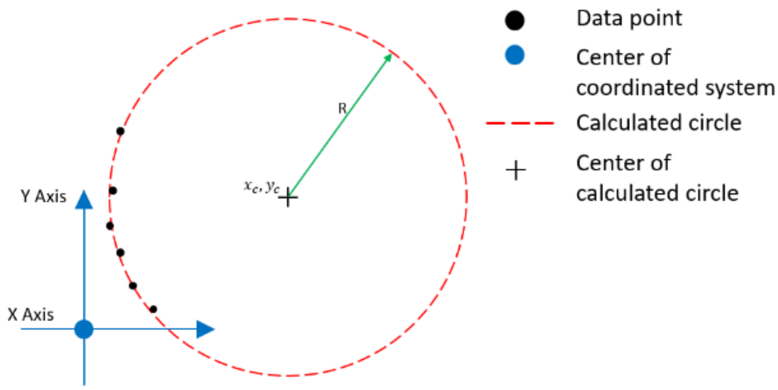


Figure 4-8. Example of Least-Square Circle fit method [162]. The left side table shows the data used for the example in coordinates (x,y) and (u,v). On the right side, a visualization is shown of the circle which fits to the points given and presents an idea of the center of the circle and its radius.

4.3.3. Depth Calculation

Once the coordinates of the origin of the circle and its radius have been computed, the remaining parameter to find is the depth, Figure 4-4-3. For this purpose, the projection of each point in the boundary needs to be checked to confirm which is the lowest value on the z axis. Thus, the next step is to iterate through all the points (P_{ij}) in the boundary (B_{top}) and find those points that have the same value for (x_{ij}) and (y_{ij}), and save the (z_{ij}) value in a temporary variable called (z_{temp}); but, each time, a new point (P_{ij}) with a (z_{ij}) value is found below the current (z_{temp}), this variable is updated.

Lastly, once all the points in (B_{top}) are processed, the difference between the height of the body (maximum value on z) and the (z_{temp}) is calculated, which represents the depth of the current geometry. A visual representation is presented in Figure 4-99, where the left cylindrical geometry shows the projected points with the dashed lines, and the right prismatic body does the same, but notice it skips the points in the middle of the object as the logic looks for the lowest value and not just the next point. In the case of the CLT panels, this projection works correctly because all the operations do not require to interact with middle points.

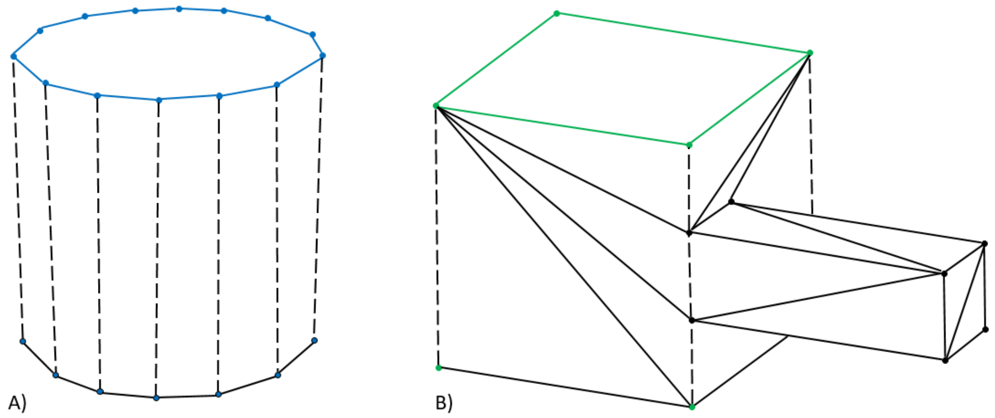


Figure 4-9. Projection of the top boundary on the bodies for the calculation of the depth. A) cylindrical object, and B) prismatic object.

4.3.4. Radius Comparison and Drilling Path

At this point in the proposed method, all the parameters of the cylinder are known, that being its center coordinates (x, y, z), its radius, and its depth (see Figure 4-4-4). Hence, it is necessary to decide which operation will take care of the geometry here. There are two different alternatives for this. First, if the cylinder has a radius of 8 mm, the standard hole for this timber object is processed as a drilling operation. Additional drilling hole diameters could be included in this process if necessary; however, for the moment, the method is constrained to only a radius of 8 mm drill bit. On the other hand, in case the diameter of the cylinder does not correspond to the drill bit, it must be processed with an end mill tool. So, for the drilling operations, the first step is to find the target to form the path for the robotic station (see Figure 4-4-5). The drilling path only requires four targets as shown in Figure 4-10, where the main axis in use is z. The initial target must be in the center of the hole but with additional clearance for the robot to locate itself in the center of the drilling hole, as this helps with collision avoidance. The target is calculated using the x and y coordinated of the hole but adds 30 mm to the z axis ($x_c, y_c, z_c + 30$). The next target is located in the center point of the found hole (x_c, y_c, z_c). Then, similarly to the initial target, the next coordinate is only modified in the z axis with the depth of the hole (z_{depth}), however, this depth is limited to 90 millimeters, constraint given to safeguard the integrity of the tool. This third target defines the drilling depth of the hole. The final target keeps the center coordinates in x and y but adds 10 millimeters of clearance for the robot to move to the next operation ($x_c, y_c, z_c + 10$) . Now with the target-path of the drilling process, it is needed to define which robot will take care of the operation, where the criteria are closed to the y_c coordinate of the cylinder. If the y_c is below the half of the limit in y ($\frac{y_{limit}}{2}$), it Is considered that the first robot (R_1) will drill the hole. Otherwise, if the y_c value is equal to or above the middle point on y, the second robot (R_2) will have this operation.

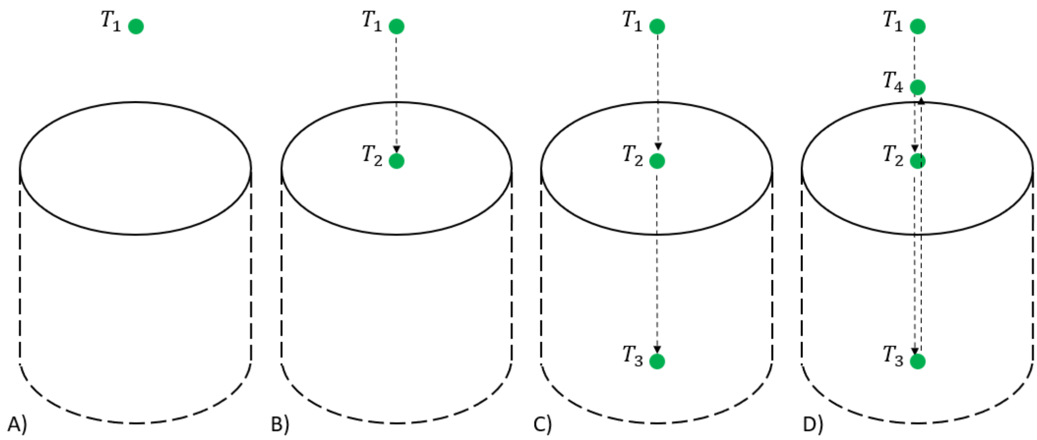


Figure 4-10. Sequence for the four targets required in the path of the drilling operation. A) first target with clearance for the robot, B) second target on the initial point of the drilling hole, C) target on the depth of the hole but limited to 90 mm, and D) target with enough clearance for the robot to switch to the next operation.

4.3.5. Circular Milling Path

In case the radius of the cylindrical body is above 16 mm, the object is processed with a milling operation, Figure 4-4-6. The path required for this process is visualized in Figure 4-11, where it is shown how the circle is divided into multiple points along the circumference, and the circles change depending on the radius and the depth increment (h). The sequence reduces the radius until it reaches the center of the cylinder, and on each interval, a series of points are generated for the circle. These steps are repeated by changing the (z) value with decrements of (h) until it reaches the bottom of the hole. As a note, the machining of the geometry beginning from the outside edge was selected as all the operations in the method are considered rough cutting or machining, and this convention could change depending on the desired surface finish, or even considering 2.5D machingin [163].

The first parameter to define this path is the angle increment (β) among points which is defined by the equation (19), where (M) is the number of points desired per circle. (M) is taken with a value of 20 in this study as it was shown to be enough points for a smooth transition in the circumference. Then, starting with (γ) with a value of zero, the accumulative angle in the circumference, x, and y value is defined for the coordinates of the points with the equations (20) and (21), where (x_c) and (y_c) are the coordinates of the center of the cylinder. The angle (γ) adds (β) and calculates the coordinates of each point until (γ) reaches 360°. Then the radius is reduced to 25 mm, the diameter of the end mill tool, and repeats the calculation of all the points in the new circumference until it reaches a radius below 12.5 mm and leaves a target in the center as a closing point. Once the center of the circle is completed, the z value changes with a decrement of (h), usually 10 mm, until it reaches the bottom depth of the milling hole or 90 mm in depth. This value is defined to keep the integrity of the end mill bit. It is important to mention that, similar to the drilling path; one target is defined with an offset of 30 mm above the surface to give enough space for the robot to set itself in position for the starting and ending point of the sequence.

$$\beta = \frac{360°}{M} \tag{19}$$

$$x = r\ \cos\gamma + \ x_c \tag{20}$$

$$y = r\ \sin\gamma + \ y_c \tag{21}$$

Now that the path of the circular milling hole is defined, the only remaining parameter to calculate is the robot assignment, which will use the same criteria as the drilling operation. The (y_c) value of the center point of the cylinder will define if the cutting process will be done by (R_1) or (R_2).

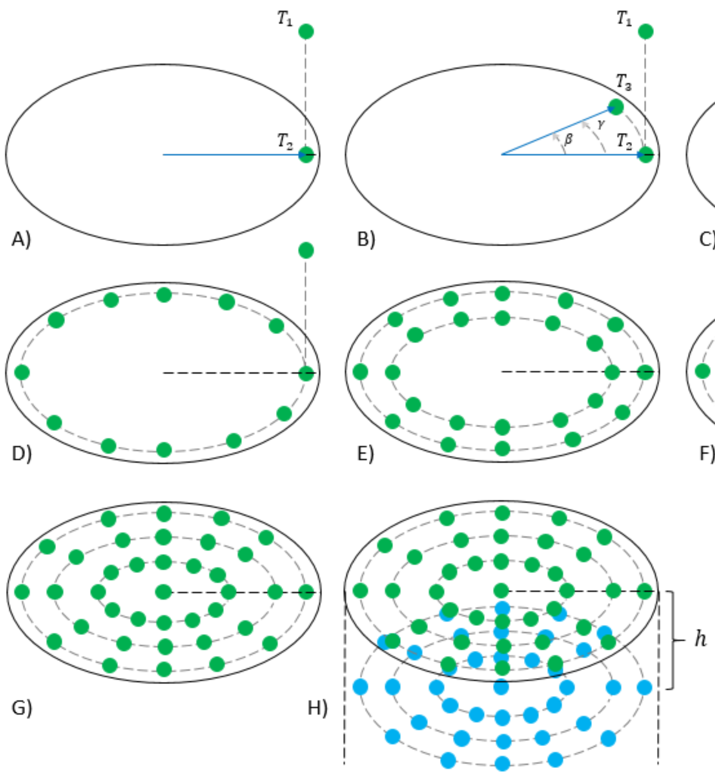


Figure 4-11. Sequence for the targets required in the path of the milling operation for cylindrical objects. A) Initial target above the surface, and first target of the bigger circle, B) third target along the circle of current radius with an increment of β angle, C) forth target with an increment of β angle but a total of γ degrees, D) illustration showing all the targets generated for the first circle of the path, E) visualization of the targets for the next circle, F) visual aid of all the targets on the circles of the milling hole excluding the center point, G) targets now including the center closing point, and H) all the targets required for one height of the milling circle and all the targets for the next height with a delta of h.

With the circular object already processed for either drilling or milling operation, the next steps are saving the cutting objects and removing the body from the current iteration object (B_i). All the paths are saved as cutting objects in a general array (C_i), where each object has 3 properties, the type of operation, the robot assigned, and the path or array of targets. Therefore, a cutting object will look like equation (22), where (m) represents the "milling" operation, (R_1) represents the robot assigned, and equation (23) represents the array of targets that conform to the path. Then, with the cutting object already saved, it is remaining to remove the cylindrical body from the object

(B_i). For this, a temporary cylindrical body (C_t) is generated with the calculated parameters, radius, depth, and center coordinates of the top circle detected; subtract the cylinder from the current iteration using equation (24), and keep the result of the iteration. The analysis of the remaining objects will be taken in a further step of the method.

$$[m, R_1, (T_1, T_2, T_3, \dots T_n)^T] \tag{22}$$

$$(T_1, T_2, T_3, \dots T_n)^T \tag{23}$$

$$B_i - C_t \tag{24}$$

4.3.6. Edge Simplification

Returning to the other side of the branch from the previous decision, where the top surface geometry was found as a circle, those prismatic objects will be analyzed. The first step here is the optimization of the boundary for those cases where the top surface is considered prismatic. Unfortunately, the "trimesh" library is not optimized, and the bodies obtained from the boolean operation could include excessive points for simple shapes; see Figure 4-12-A for an example of overcrowded mesh. Thus, an optimization of the top boundary is required, Figure 4-4-7. For this procedure, a quick iteration between all the edges that form the boundary is implemented, where the angle between them is calculated, and those with 180° are unified, see Figure 4-12-C. This iteration continues until no straight angle is found, leaving a simplified boundary for the rest of the study.

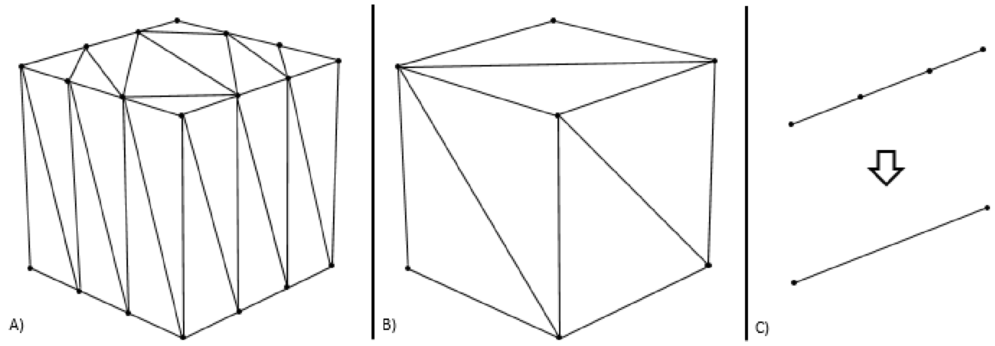


Figure 4-12. Example of simple geometry with overcrowded mesh. A) Simple cube with excessive mesh points, B) cube with simplified mesh, and C) example of multiple segments optimized to single line.

4.3.7. Middle Plane Line

These prismatic geometries have two cutting options, end mill machining or circular sawing. To define which process will be used, first, it is required to find the depth of the current boundary, where the same function required for the cylindrical objects is used, see Figure 4-9. In case the depth of the body does not cover the entire thickness of the panel or the maximum (z) value, the geometry will be processed with the end mill. However, there is a condition to review before calculating the path for the milling process, the intersection of the middle plane on the y axis. Some cavities required in CLT panels are long enough and cross almost the entire panel in the y axis; yet, as the robots are physically constrained in this axis, it is necessary to split the geometry in two, so each robot can handle its own part, Figure 4-4-8. The process of splitting the top surface is shown in Figure 4-13, where the first step is to create a reference line between two points in the middle of the panel. These points are declared as (25) and (26). Then, each edge (E_k) of the surface is checked, and the y value of the conforming two points from the edge is compared. If both points are on the same side of the panel, either above the middle line (27) or below, they are considered to not have an intersection with the middle plane; but, when they are found on different sides, the edge (E_k) is declared to have an intersection, and the point crossing the two lines is calculated. The form of the lines is (28), where A, B, and C are the numbers that define the line. To calculate these coefficients, Equations (29), (30), and (31) are used, where the coordinates of the points are given by the two lines to review, the reference line and the crossing edge (E_k). Therefore, two lines are given by the equations (32) and (33). The next step is to simply solve the linear equations to find the coordinates (x, y) of the crossing point (I_1). The current edge is split then into two edges with this new intersecting point as one end, leaving the original points as the counter ends of the lines, see Figure 4-13-C and D. This process is repeated on all the edges of the surface, following a clockwise convention until there is no intersecting line. Once the two intersecting points (I_1 and I_2) are found, and the lines split, the surface is checked again in a clockwise convention but now closing the boundaries between the two new points, see Figure 4-13-G and H, leaving two surfaces instead of one.

$$P_{r1} = (0, \frac{y_{limit}}{2}) \tag{25}$$

$$P_{r2} = (x_{limit}, \frac{y_{limit}}{2}) \tag{26}$$

$$(\frac{y_{limit}}{2}) \tag{27}$$

$$Ax + By = C \tag{28}$$

$$A = y_2 - y_1 \tag{29}$$

$$B = x_1 - x_2 \tag{30}$$

$$C = Ax_1 + By_1 \tag{31}$$

$$A_1x + B_1y = C_1 \tag{32}$$

$$A_2x + B_2y = C_2 \tag{33}$$

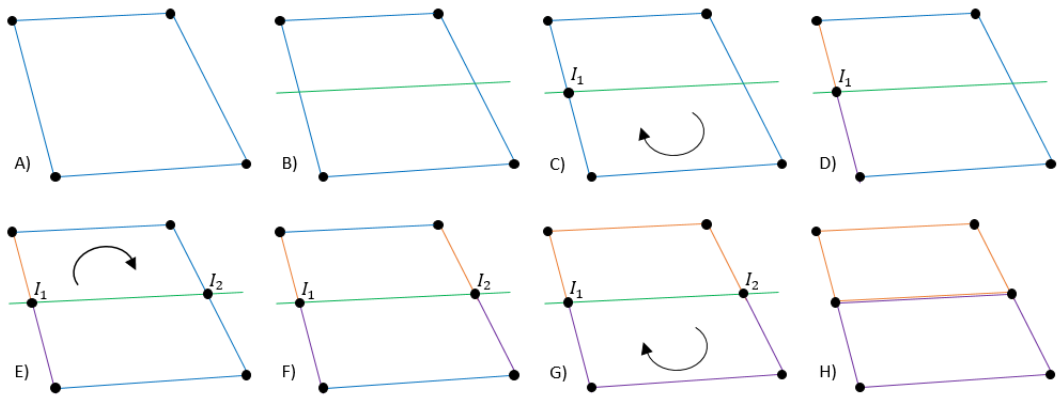


Figure 4-13. Sequence of steps required to split the top boundary intersecting the middle plane of the CLT panel. A) original boundary, B) boundary crossing the middle plane of the panel, C) intersecting point I_1 found between the first edge crossing the middle line, D) line split in two using the new I_1 point as middle point, E) second intersecting point I_2 found, F) second line split in two using the new intersecting line, G) separation of edges per new boundary depending from the side of the line, and H) two new boundaries closed with lines using the intersecting points (I_1 and I_2).

4.3.8. Milling Path

Subsequently, it is necessary to find the centroid for the development of the path in the end mill process, Figure 4-4-9. In each of the surfaces, the boundary is a polygon which is considered a composite shape, and the centroid is given by the average centroid of all the geometries inside the boundary. Fortunately, the nature of the STL format has triangular meshes on all the facets; thus, getting the centroid of the polygon of the top surface is obtained with the average of all the tringle's centroids in the surface. The equations used are (34) and (35), where $(\overline{y})$ is the centroid coordinate of the polygon in the (y) axis, $(\bar{x})$ is the centroid coordinate of the polygon in the (x) axis, (A_n) is the area of the triangle, (x_n) is the centroid coordinate of the triangle in the (x) axis, and (y_n) is the centroid coordinate of the triangle in the (y) axis. The centroid coordinates of one single triangle are given by Equations (36) and (37), which use the coordinate of the three vertices conforming to the triangle, and its area is calculated following Equation (38), where (x_i) and (y_i) are the coordinates of the three vertices of the triangular facet F_j. It is shown in Figure 4-14 the process of calculating the centroid of a square conformed by two triangles, where the green point of the "C" illustration represents the centroid of the entire square, and it is the result of the average from the two purple centroids in the triangles from the "B" picture.

$$\bar{x} = \frac{\sum A_n X_n}{\sum A_n} \quad (34)$$

$$\bar{y} = \frac{\sum A_n y_n}{\sum A_n} \quad (35)$$

$$x_n = \frac{x_1 + x_2 + x_3}{3} \quad (36)$$

$$y_n = \frac{y_1 + y_2 + y_3}{3} \quad (37)$$

$$A_n = \left| \frac{x_1 y_2 + x_2 y_3 + x_3 y_1 + y_1 x_2 + y_2 x_3 + y_3 x_1}{2} \right| \quad (38)$$

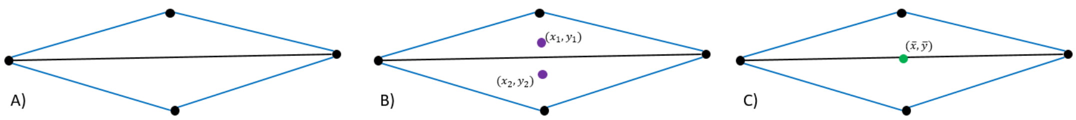


Figure 4-14. Example of simple geometry with overcrowded mesh. A) Simple cube with excessive mesh points, B) cube with simplified mesh, and C) example of multiple segments optimized to single line.

Now with the centroid of the geometry, it is needed to find the path for this surface, and the steps for this is like the cylindrical machining body, but instead of a radius, a segment is used, which represent the distance between the centroid of the geometry and the points P_{ij} that form the boundary of the geometry, see Figure 4-15. Therefore, it is required to calculate the "radius" $(r_i, r_1, r_2, \ldots\ r_n)$ between the centroid and all the points of the shape. The magnitude of the radius r_i is given by Equation (39), where the coordinates $(x_c,\ y_c)$ belong to the centroid of the geometry and the coordinates (x_i, y_i) are from each of the points from the contour. In addition, an angle γ_i is calculated for each of the points using Equation (40). Then, each of these radiuses is reduced by 25 mm, diameter of the end mill tool, Figure 4-15-C to D, and the new targets of the boundary offset is calculated with Equations (41) and (42). This sequence is repeated until the radius between the points is below 12.5 millimeters, radius of the end mill tool, and a target is placed in the centroid as a closing point. Once the center of the centroid is completed, the z value changes with a decrement of h, usually 10 mm, until it reaches the bottom depth of the milling hole or 90 mm in depth. This value is defined to keep the integrity of the endmill bit. It is important to mention that similarly to the drilling path, one target is defined with an offset of 30 mm above the surface to give enough space for the robot to set itself in position for the starting and ending point of the path. Now that all the targets of the milling cut are defined, the only remaining parameter to calculate is the robot assignment, which will use the same criteria as the drilling operation. The y_c value of the centroid point of the geometry will define the robot (R_1 or R_2) for the cutting process.

$$r_i = \sqrt{(x_i - x_c)^2 + (y_i - y_c)^2} \tag{39}$$

$$\gamma_i = \tan^{-1}(\frac{y_i - y_c}{x_i - x_c}) \tag{40}$$

$$x_i = r_i \cos\gamma_i + x_c \tag{41}$$

$$y_i = r_i \sin\gamma_i + y_c \tag{42}$$

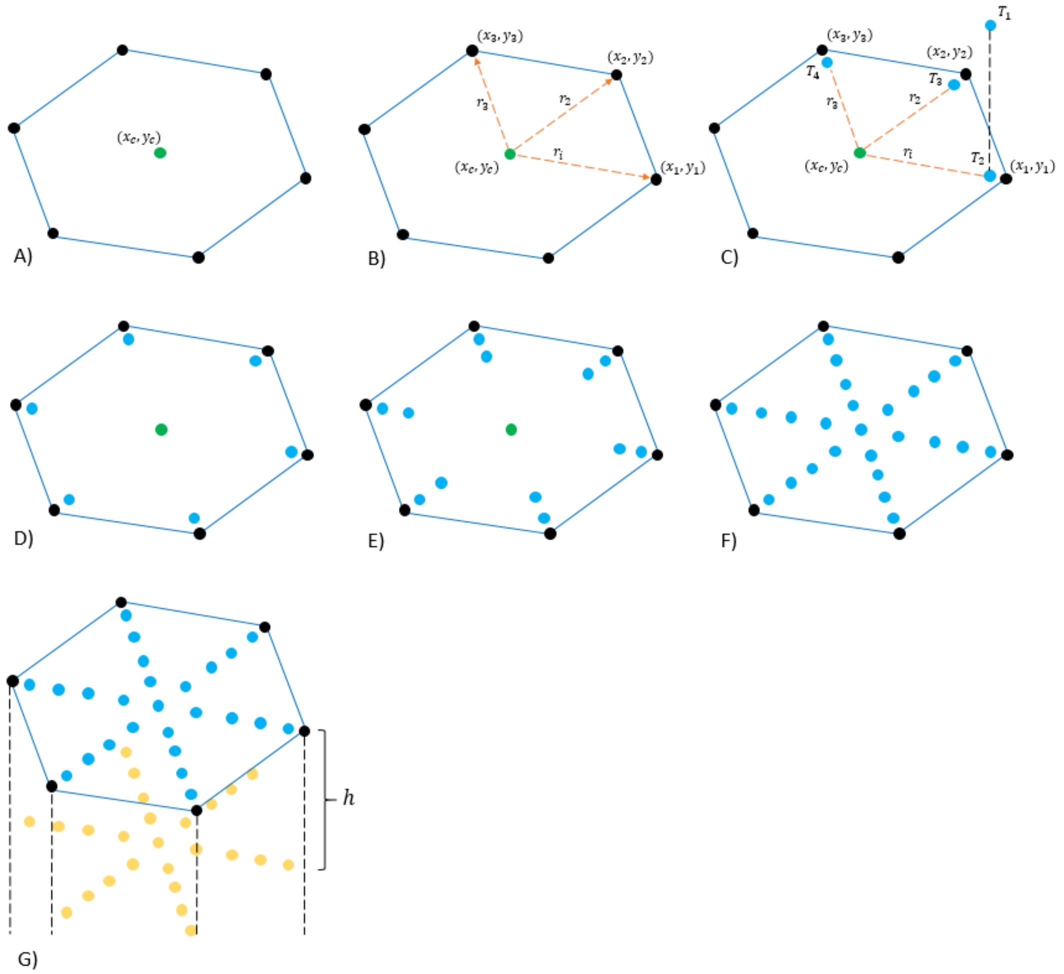


Figure 4-15. Sequence of targets for the path of a polygon-based body. A) Initial surface with the centroid of the polygon, B) radiuses calculated between the centroid of the polygon and each point of the boundary, and C) first radiuses of the geometry reduced by 25 mm and initial starting point, D) first set of targets of the polygon, E) second set of targets of the polygon, F) all sets of targets for one height, and F) targets generated for a different height with a decrement of h in z axis.

4.3.9. Circular Saw Path

Once all the paths are generated for the bodies with a depth not covering the entire thickness of the CLT panel, it is required to go back to the opposite ramification. In this case, where the depth covers the full height of the panel, there are two possibilities for the machining process, using a circular saw or an end mill. The initial analysis is to define which lines (E_k) of the top surface (F_j) are internal or external, where internal lines mean both points (P_{ij}) conforming the line are inside the panel and not on the border, while external lines mean exactly the opposite. All the lines (E_k) of the surface (F_j) are simply inspected to check if their points are within the outer limits of the panel, (x_{limit}, y_{limit}, z_{limit}). Then, the exterior lines are ignored for this time as they do not require any machining process, and the length of all of them is examined. The equation (43) is used to determine the length, where the coordinates (x_{ij}, y_{ij}, z_{ij}) of both points (P_{i1}, P_{i2}) conforming the lines are used in the equation, while the values in the z axis are ignored. In case the length of the internal lines is below 200 mm, the minimum distance required for the circular saw operation, the body is processed as an endmill machining process, and the procedure to determine the path and the robot is the same as explained above.

$$l_{ij} = \sqrt{(x_{ij+1} - x_{ij})^2 + (y_{ij+1} - y_{ij})^2} \quad (43)$$

On the other hand, when the length of the lines is above 200 mm, the body is processed as a circular saw operation, and the path required is less complicated, Figure 4-4-10. There are two diameters for the circular saws in the robotic station, one of 500 millimeters and another one of 10 inches. Therefore, if the length of the line in the process is above 600 millimeters (diameter of a bigger saw plus 100 mm of clearance), the 500 mm saw is considered the current tool. Otherwise, the tool used is one of 10 inches. Now, only 4 targets are required per line, the starting point, two points indicating the actual cutting line, and the closing point. To get these points, it is required to iterate through all the internal lines of the top surface in a clockwise orientation. First, the angle is calculated by taking as reference the points of the line and the equation (38). Then, the equations (44) and (45) are used to get the coordinates of the first target or first point (P_1), where R_{saw} is the radius of the current circular saw, $P_{i1}(x)$ is the x value of the first point and $P_{i1}(y)$ is the y value of the first point. For the second point (P_2)

similar equations are used, but instead of only using the radius of the saw, the difference with the length of the line (l_{ij}) is used, which gives equations as follows (46) and (47). The starting and ending points remain, but both will have the same coordinate of the points (P_1, P_2) correspondingly with the difference of an offset in the z axis, which is the sum of the radius of the saw plus 30 mm of safety clearance. A clearer visualization is shown in Figure 4-16**,** where the targets are generated in a clockwise rotation, and the red line is excluded for being an exterior line.

$$x_1 = R_{saw} \cos \gamma_i + P_{i1}(x) \quad (44)$$

$$y_1 = R_{saw} \sin \gamma_i + P_{i1}(y) \quad (45)$$

$$x_2 = (l_{ij} - R_{saw}) \cos \gamma_i + P_{i1}(x) \quad (46)$$

$$y_2 = (l_{ij} - R_{saw}) \sin \gamma_i + P_{i1}(y) \quad \text{c(47)}$$

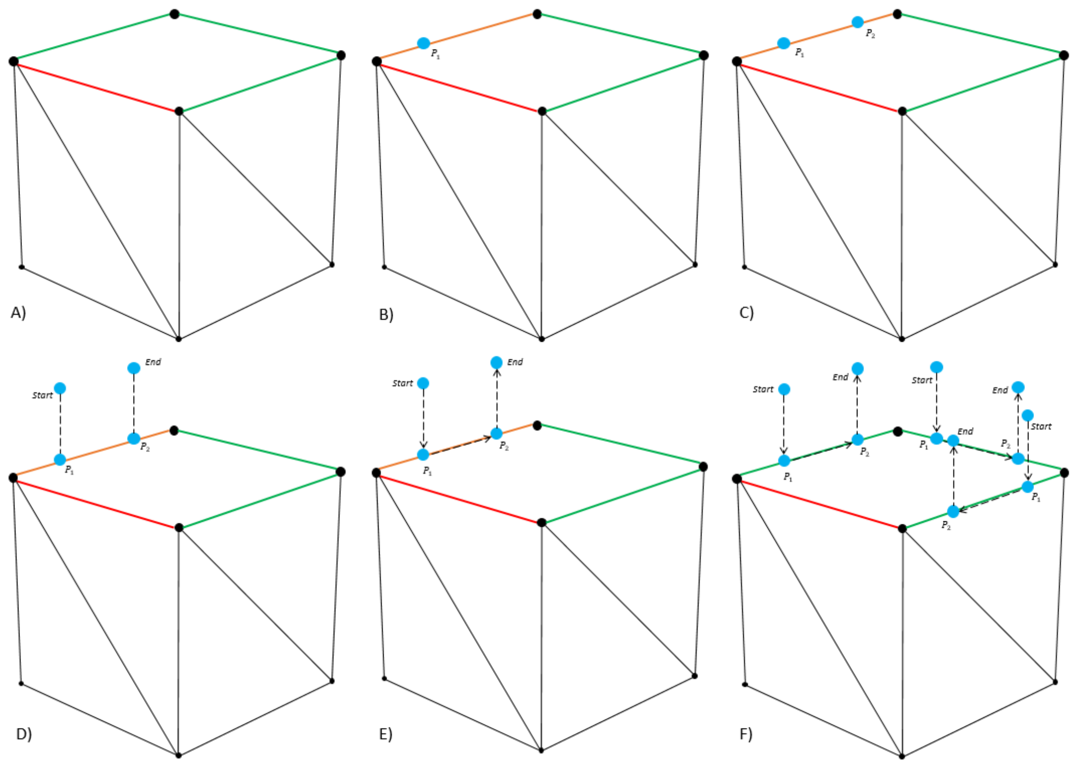


Figure 4-16. Sequence of sawing process for the top lines. A) identification of the external line highlighted in red, B) identification of the start point for one line, C) identification of the end point for one line, D) generation of the targets in an z offset for safety position of the robot, E) target path generated following the points created, and F) paths created on the rest of the remaining lines.

In addition to the sawing cuts of the top surface, it is necessary to consider the side cuts required for the geometry. Not all the objects have lateral sawing cuts. Only those with an external line have them, and when this scenario comes up, the cutting paths must be addressed. For this, both end points are taken from the external lines as reference for the generation of the targets, see Figure 4-17. The first target generated uses the same coordinates of the reference point but adds an offset of the radius of the saw and 30 mm additional safety clearance. The second target uses the same coordinates of the reference point minus the depth of the body in the z axis. The third target is placed at the same height as the second target, but its x and y coordinates are a projection from the next coincident line in the boundary, which is not the external line.

With this, a target is obtained, which is aligned with the shape of the polygon. Finally, the fourth target is placed in the same coordinates as the third point, but it has the height of the first target. The robot assignation is given with the (y) value similar to the drilling process, and the sequence just explained is repeated for the second end of the external line. This sawing process produces two cutting objects, which are then appended to the general array (C_i).

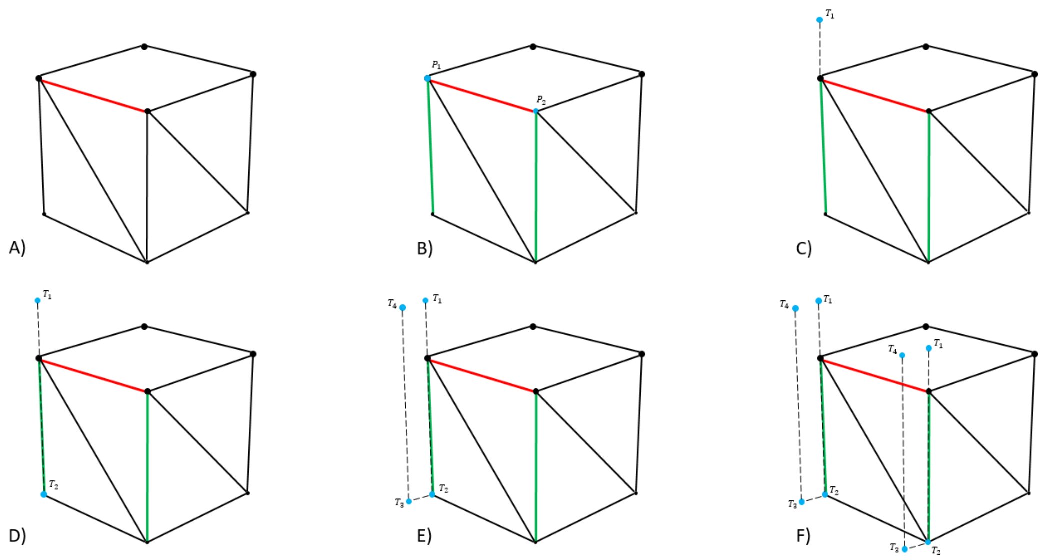


Figure 4-17. Sequence of sawing process of the side cuts required in external lines. A) identification of the external line highlighted in red, B) identification of the two end points of the external lines, C) generation of the first target in an z offset, D) second target generated in the bottom of the panel, E) third and the fourth target generated in a projection of opposite direction of the next line in the boundary, and F) target path for both reference points.

4.3.10. Body Subtraction

Now that the polygon geometries have been processed, either for sawing or milling, the following step is to remove the current body from the iteration object (B_i), and to save all the targets in the general array (C_i). Therefore, a temporary polygon body (P_t) is generated for this operation, Figure 4-4-11. This temporary body is created with the extrusion of the top surface geometry by the depth calculated previously; see

Figure 4-18 for a clearer illustration. The direction of the extrusion is upside down, and the result will be overlapped with the current object. Once this new temporary body is created, a boolean subtraction from the current object is implemented, $B_i - P_t$. The result of this boolean operation can have two outcomes, one where the entire iterative object (B_i) is eliminated; or a residual body with no face touching the top surface, Figure 4-4-12. This operation is required because there are machining operations missing for the sides of the CLT panel, which will be untouched without this step. This remaining body is processed with a milling tool as it is the only utensil that can reach these cavities. However, now the boundary to consider while extracting the path of the process belongs to the side face, which is on the border of the wood panel. Therefore, all the steps required for milling an object are repeated (identification of the boundary, calculation of depth, calculation of centroid of the polygon, and targets generations) but in the opposite direction of the normal vector from the side face. The robot designation of this cutting object is given by the (y) value of the centroid.

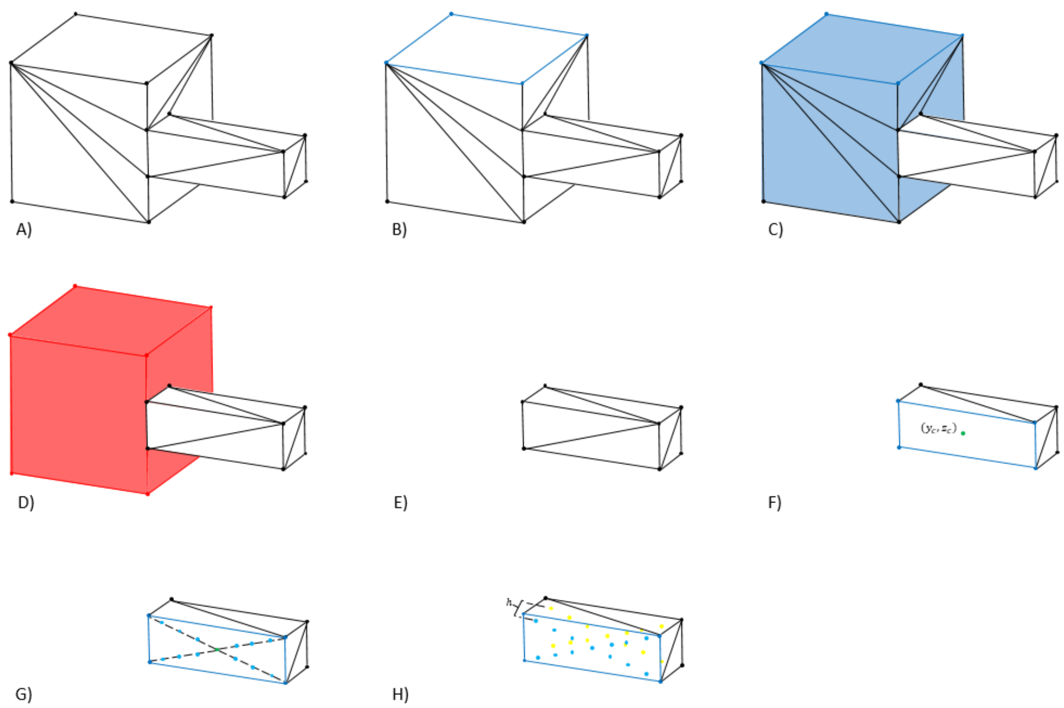


Figure 4-18. Sequence of the extrusion and boolean operation in the iterative object (B_i). A) Starting body for the iteration, B) Top surface boundary recognized, C) Geometry extruded by the depth found and body overlapped with the current object, D) the red highlighted body represents the subtraction of the boolean operation, E) the remaining part of the body after the subtraction operation, F) the new boundary on the side surface of the object and the centroid calculated, G) first targets generated for the milling process, and H) second targets generated in the opposite direction of the normal vector with an increment of h.

Then, the new cutting object is saved in the general array (C_i) and a side object is removed from the iterative object (B_i) following the same concept of the previous extrusion but in the opposite direction of the normal vector of the side surface. The iterative object must be empty at this point of the method, and all the steps are repeated thru all the objects (B_i) from the original Boolean operation. The method ends when there are no more objects to process, and all the cutting objects are now in the general array (C_i), Figure 4-4-13.

4.4. Results and discussion

A schematic of the virtual design of a robotic machining process for CLT panels is shown in Figure 4-19 [164]Click or tap here to enter text.. This station is designed on the software RobotStudio®, which contains real-world representative data and gives a realistic performance simulation based on ABB robot models and controllers. To validate the automatic target-path planning system proposed, this station is used as a case study, and the board design used is the one shown in Figure 4-6. The paths generated from all the cutting objects are plotted to confirm the methodology's position and desired order, see Figure 4-20. In this visual aid, it is possible to see in diverse colors the lines representing different paths depending on the type of tool and robot. For instance, the end mill operation for robot 1 is shown in green color, and it is possible to see that it covers the circular cavity and the rectangular pockets from the bottom side of the picture. On the other hand, the blue lines represent the circular sawing operation of 500 millimeters for robot 2, and they are displayed on the top side of the picture in the windows and the diagonal cut from the corner.

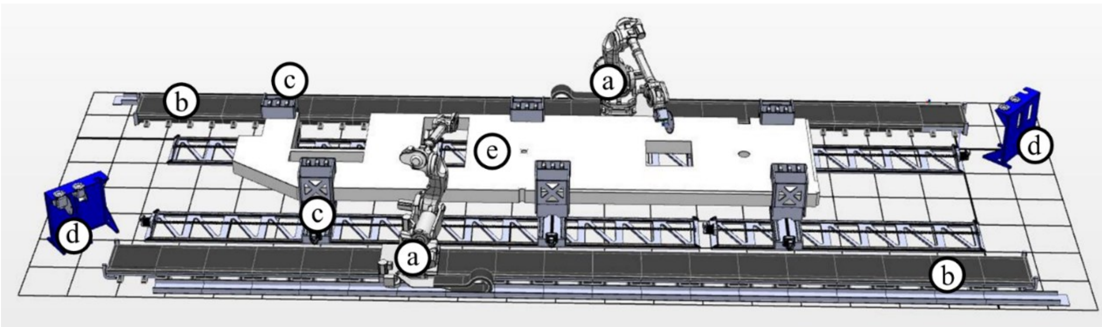


Figure 4-19. Automated robotic machining cell for cross-laminated timber panels: (a) Robot ABB® IRB 7600; (b) Track motion ABB® IRBT 7004; (c) Flexible clamping System; (d) Tool stand; (e) CLT Panel for reference.

Additionally, it is possible to see the split of lines in geometries crossing the middle line of the panel, as the big window in the middle of the panel with red and blue paths on the same edge, highlighting the need for both robots to fulfill the sawing operation. Moreover, it is critical to mention the processing time of 47.95 seconds required by the method TPPM for the generation of the entire paths and cutting objects. This script was run on an off-the-shelf windows desktop computer with a processor Intel® Core™ i5-7400 and 16 GB of ram. This processing time is an incredible enhancement for getting the machining paths of the CLT panel, and there is no comparison against the hours required by human experts who would manually get every single operation.

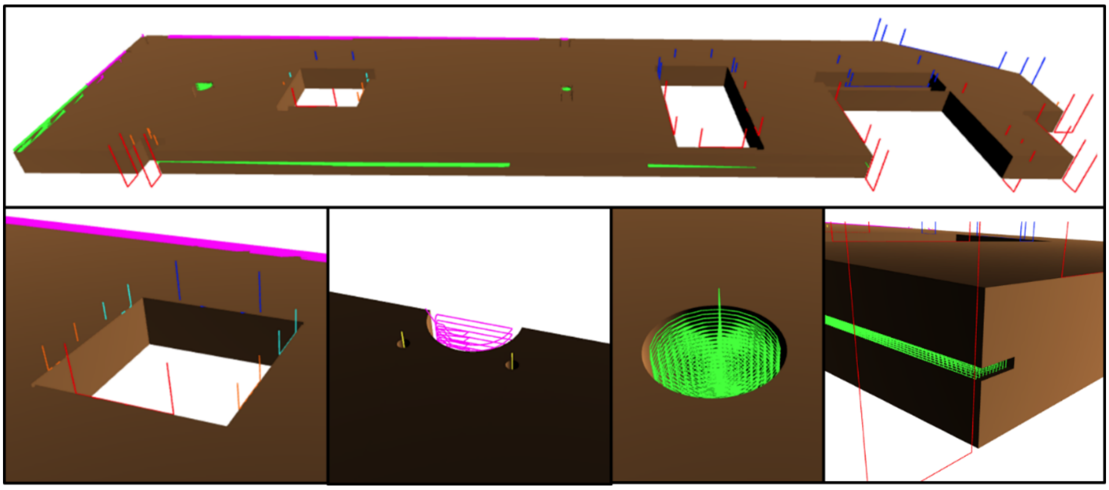


Figure 4-20. 3D plot of CLT panel with paths generated by the algorithm TPPA. The color code of the lines represents different operations and robots. The color code for robot 1 is green for end mill, aqua green for drilling, orange for the circular saw of 10 inches, and red for circular saw of 500 millimeters. Color code for robot 2, pink for end mill, yellow for drilling, light blue for the circular saw of 10 inches, and blue for circular saw of 500 millimeters.

Another way to visualize the obtained paths is by printing the cutting objects saved in the general list (C_i). An example of the cutting objects can be seen in Figure 4-21, where the parameters of some of these objects are displayed, ID, operation type, tool, robot assigned, and an array of target coordinates that conforms to the path. This list of cutting objects is shared with the API of RobotStudio ® for its usage depending on the best options for the machining operation. They could be used depending on the preference of the third party or the expertise of the programmer. The cutting objects could be grouped to assign one single type of machining operation and avoid the time wasted on tool changing, or operations could be sorted depending on the proximity of each path. Either way, the flexibility for using the cutting objects depending on the desired outcome is there; yet, this procedure is not included in the study as this is out of the current scope.

```
Cut ID:11, Operation Type:lineal, Tool:saw500, Robot:R1
Path \(x,y,z\) :
      [12000.0, 750.0, 575.0]
      [12000.0, 750.0, 315.0]
      [12000.0, 251.0, 315.0]
      [12000.0, 251.0, 575.0]
Cut ID:12, Operation Type:lineal, Tool:saw500, Robot:R1
Path \(x,y,z\) :
      [9700.0, -19.0, 565.0]
      [9700.0, -19.0, 315.0]
      [9700.0, -19.0, 0.0]
      [9700.0, -249.0, 0.0]
      [9700.0, -249.0, 565.0]
Cut ID:13, Operation Type:lineal, Tool:saw500, Robot:R1
Path \(x,y,z\) :
      [11300.0, -19.0, 565.0]
      [11300.0, -19.0, 315.0]
      [11300.0, -19.0, 0.0]
      [11300.0, -249.0, 0.0]
      [11300.0, -249.0, 565.0]
Cut ID:14, Operation Type:lineal, Tool:saw500, Robot:R1
Path \(x,y,z\) :
      [9700.0, 1250.0, 575.0]
      [9700.0, 1250.0, 315.0]
      [9700.0, 251.0, 315.0]
      [9700.0, 251.0, 575.0]
Cut ID:15, Operation Type:lineal, Tool:saw500, Robot:R1
Path \(x,y,z\) :
      [11300.0, 251.0, 575.0]
      [11300.0, 251.0, 315.0]
      [11300.0, 1250.0, 315.0]
      [11300.0, 1250.0, 575.0]
Cut ID:16, Operation Type:lineal, Tool:saw500, Robot:R2
Path \(x,y,z\) :
      [9950.0, 1500.0, 575.0]
      [9950.0, 1500.0, 315.0]
      [11050.0, 1500.0, 315.0]
      [11050.0, 1500.0, 575.0]
Cut ID:17, Operation Type:drilling, Tool:drill bit, Robot:R2
Path \(x,y,z\) :
      [70.71067817651804, 2929.2893243064495, 335.0]
      [70.71067817651804, 2929.2893243064495, 315.0]
      [70.71067817651804, 2929.2893243064495, 225.0]
      [70.71067817651804, 2929.2893243064495, 325.0]
Cut ID:18, Operation Type:circle, Tool:endmill, Robot:R1
Path \(x,y,z\) :
      [1499.9999999274155, 1612.5000137037432, 365.0]
      [1499.9999999274155, 1612.5000137037432, 315.0]
      [1534.7644160422365, 1606.993871114188, 315.0]
      [1566.125848889809, 1591.0144229457394, 315.0]
      [1591.0144229150615, 1566.125848920487, 315.0]
```

Figure 4-21. Partial print of cutting objects showing the operation type, tool, robot assigned and target-path.

Now, the computer aid method TPPM developed in this study is effective and automates the task that otherwise would take hours for an expert to fulfill. However, there are areas of opportunities for the current method, like the optimization of the paths and not just the generation of them through geometrical analysis. Similar to Wulle [149]Click or tap here to enter text., the algorithm could be time optimized when looking to reduce the number of movements and its continuity between operations; or, following the study of Ma [150], the planning method could consider the cutting force fluctuation in the tools in order to improve the finishing quality. These studies are only some examples of the opportunity for optimization missing in the study. On the other hand, the current method can only process primitive geometries, like cylinders, rectangles, or triangles. These are the most common shapes required in the industry, yet they limit the creativity of developers. Thus, another improvement in the methodology will be the inclusion of free-form surfaces like the study made by Dhanda [147]. Including this feature will give a closer step on the full automation of the path generation and will use the entire potential for machining of industrial robot station. Also, it would be desirable to have the method of this study, TPPM, integrated directly into the developer's software, like BIM, as this will reduce the bridge between manufacturing and design, which relies on experts right now.

4.5. Conclusion

Offsite construction with CLT as the material is a trend in the industry and closing the bridge between automated manufacturing for the desired boards and the developer's designs is a research area with demand to enhance productivity. Therefore, this article has provided a target-path planning method (TPPM) for an automated robotic machining station, closing the research gap of automatic path planning for 3D CLT panels, selection of tools, and manufacturability of the system. The method from this study can process an entire cross-laminated panel and generate the paths required with geometrical analysis. Depending on the primitive geometry, cylinders, rectangles, and others, it decides the type of tool and generates the targets required for robots in the machining station. For cylinders, it calculates the center coordinates, radius, and depth, to, later on, decide if the operation must be machining or drilling. On prismatic elements, it first checks if the geometry crosses the middle line and splits the element if it does. Then, the method measures the edges on the top surface and considers the depth of the body; so it can decide if the machining operation should be an end mill or a circular saw of 500 mm or 10 inches. The method is highly efficient, less than 48 seconds for processing one entire CLT panel when compared to the manual planning of knowledgeable experts, which can take hours for one single board. This article has provided a step forward against the full automation of CLT manufacturing, but there is future work still pending. One of the improvement opportunities for the target-path planning methods is the integration of free-form surfaces instead of the limited primitive geometries. This will allow architects and engineers to design a complex-shape building that can be machined automatically. Another topic for future work is the optimization of the method. As mentioned in the “related work” section, the method could be optimized in different ways, like finding the fastest path to the machine or reducing the cutting forces of the robot. Additionally, one of the limitations still to consider is the automation of the flipping operation for the extensive size and heavy CLT panels, as the current method only processes one side of the material, and the flipping operation remains manual. Plus, the direct integration of the TPPM into software like BIM will help developers know their design's manufacturability without further steps or unnecessary time. Moreover, a case study of one CLT panel with a real-life scenario is still pending to compare and validate the simulation with RobotStudio ®. Part of the features pending of this study is the interaction of the automatic station with the clamping mechanism and the ergonomics of the robots when dealing with each operation. The preceding features are needed to fulfill the complete automation of the manufacturing of CLT buildings, yet this study has made progress toward intelligent manufacturing.

Chapter 5. Conclusion

5.1. General Conclusion

The construction industry has been improving in the last years in multiple areas; enhanced materials, logistics, simulations, and others, are examples of research topics. Yet, when discussing sustainability, off-site construction seems to be the main option as it can take advantage of manufacturing features in a controlled environment. Additionally, mass timber construction requires the usage of off-site construction because the fabrication of structural elements will be absurd and wasteful to be made in-site. Cross-laminated timber has been the common material for mass timber. This thesis intends to delve into possible improvements from a manufacturing perspective, especially emphasizing Industry 4.0, or the now-called Construction 4.0. In the second chapter of this thesis, a scientometric comparison is made between construction and Industry 4.0 for CLT. This analysis was implemented to understand the manufacturing research gaps in this field. Among the findings of this review, it can be said that cross-laminated timber became popular for structural elements and researchers after 2015 when the IBC accepted the material; and that Industry 4.0 can be considered infant in terms of CLT for construction. Nevertheless, it was clear that the manufacturing field lacked two topics for CLT: a digital twin and its automation. On the other side, the third chapter develops the design and simulation of an industrial robot machining station for cross-laminated timber. This machining station is the first effort for the development of a digital twin, but its validation in a real case study is pending. The system included an independent designer for a flexible clamping station needed for the wide variety of CLT panels, and it was validated through a simulation in RobotStudio®. Finally, in the fourth chapter, a target-path planning method was developed for the automation of the CLT panel machining. This method is a geometric feature-based, where it analyses each body to a machine, and depending on its geometry, the method calculates the targets, assigns the tool for the operation, and selects the robot of the machining station. The three most common operations in the industry were considered the method, drilling, end mill machining, and sawing. The machining station for CLT can be considered automated thanks to this method. In conclusion, the work done in this thesis moves a step forward in developing Construction 4.0 for cross-laminated timber.

5.2. Statement of Contribution

The chief contributions of this research are summarized below:

1. Determine the areas of opportunity for manufacturing in Cross-Laminated Timber in Industry 4.0, Digital Twin or machining station, and machining automation (Objective 1);
2. Developed a machining robotic station for CLT panels with a flexible clamping system (Objective 2);
3. Programmed and tested a Target-Path Planning Algorithm (TPPA) for the automation of CLT machining (Objective 3).

5.3. Research Limitations

This research has the following limitations:

- The discoveries found in the literature review should be considered in light of some restrains because the findings are limited by the selected keywords and the restrictions set as input in the inquiry of the academic data. Plus, questioning the reasons for the “why” and “how” of the academic documents is out of the scope of this thesis.

- The authors have no possibilities to implement in real life the digital robotic cell designed in RobotStudio. Financial and facility limitations constrain the development of the case study.
- The current path planning algorithm can only process primitive geometries, and any complex or organic shape will be avoided, and its programing will be manual.
- The implementation of the TPPA algorithm requires the usage of python language and the input of the files in STL format. Any script created can not handle other kinds of the format, and the tool developed will need to be processed for the BIM's API.

5.4. Future Research

Here are some of the opportunity areas for future research:

- The machining robotic cell requires a physical validation to compare the digital concept with a real-life study case. Similarly, the path planning of the TPPA algorithm requires validation with a real CLT panel, where the machining quality, tolerances, and performance have to be confirmed.
- The flexible clamping systems need validation with a real-life prototype to confirm the holding capacity of the system. Here is a brief list of the multiple parameters to review, holding capacity of the clamping system, surface mark in the CLT panel, machining vibration performance, and flexible re-position of the clamps.
- The TPPA algorithm takes into consideration primitive geometries, which are the most common features in the CLT panel, yet, developers and architects are constantly pushing for our-of-the-box shapes. Thus, an improvement in the

algorithm should be the automation of target path planning for free surface geometries in CLT panels.

- The target-path planning method proposed successfully automates machining primitive geometries; however, this method is not optimized. There are areas of opportunity to improve the algorithm in optimization of time consumption, tool wearing, energy consumption, and others.
- The modularization of the TPPM algorithm and the integration of a user friendly interface to select the type of machining desired, like rough or fine machining, or any optimization desired.
- The direct integration of the TPPM method as an addon tool in BIM requires research, so developers can understand the manufacturability of the CLT panels from the design phase.

References

[1] R. E. Smith, G. Griffin, T. Rice, and B. Hagehofer-Daniell, “Mass timber: evaluating construction performance,” *Architectural Engineering and Design Management*, vol. 14, no. 1–2, pp. 127–138, Mar. 2018, doi: 10.1080/17452007.2016.1273089.

[2] A. Sandoli, C. D’Ambra, C. Ceraldi, B. Calderoni, and A. Prota, “Sustainable Cross-Laminated Timber Structures in a Seismic Area: Overview and Future Trends,” *Applied Sciences*, vol. 11, no. 5, p. 2078, Feb. 2021, doi: 10.3390/app11052078.

[3] UNEP Sustainable Buildings and Climate Initiative, “Buildings and Climate Change: Summary for Decision-Makers,” 2009. https://wedocs.unep.org/bitstream/handle/20.500.11822/32152/BCC_SDM.pdf?sequence=1&isAllowed=y (accessed May 20, 2022).

[4] B. Kasal *et al.*, “Wood-Based Materials,” in *Ullmann’s Encyclopedia of Industrial Chemistry*, Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA, 2015, pp. 1–56.

[5] S. Gagnon, E. T. Podesto, and P. Crespell, “ CLT Introduction to cross-laminated timber,” *CLT handbook: cross-laminated timber*, pp. 45–57, 2013, Accessed: May 02, 2022. [Online]. Available: https://www.fpl.fs.fed.us/documnts/pdf2013/fpl_2013_gagnon001.pdf.

[6] M. S. Nordin, M. B. Norshariza, W. C. Lum, N. S. Zainal, and Z. Ahmad, “Assessment on Bonding Strength of Cross Laminated Timber Made from Light Red Meranti Manufactured by Vacuum Press Method,” 2022, pp. 999–1012.

[7] J. Ellinger, C. Beorkrem, and C. Dodson, “Computationally Derived Cross-Laminated Timber Reinforcement and Construction,” 2019, pp. 1135–1150.

[8] N. Gabriela Pereira Carvalho and E. Walmir Cazarini, “Industry 4.0 - What Is It?,” in *Industry 4.0 - Current Status and Future Trends*, IntechOpen, 2020.

[9] R. Maskuriy, A. Selamat, K. N. Ali, P. Maresova, and O. Krejcar, “Industry 4.0 for the Construction Industry—How Ready Is the Industry?,” *Applied Sciences*, vol. 9, no. 14, p. 2819, Jul. 2019, doi: 10.3390/app9142819.

[10] E. Forcael, I. Ferrari, A. Opazo-Vega, and J. A. Pulido-Arcas, “Construction 4.0: A Literature Review,” *Sustainability*, vol. 12, no. 22, p. 9755, Nov. 2020, doi: 10.3390/su12229755.

[11] W. P. J. Pemarathne and T. G. I. Fernando, “Wire and cable routings and harness designing systems with AI, a review,” in *2016 IEEE International Conference on Information and Automation for Sustainability (ICIAfS)*, Dec. 2016, pp. 1–6, doi: 10.1109/ICIAFS.2016.7946575.

[12] K. Kim, H. Kim, and H. Kim, “Image-based construction hazard avoidance system using augmented reality in wearable device,” *Automation in Construction*, vol. 83, pp. 390–403, Nov. 2017, doi: 10.1016/j.autcon.2017.06.014.

[13] P. Martinez, R. Ahmad, and M. Al-Hussein, “A vision-based system for pre-inspection of steel frame manufacturing,” *Automation in Construction*, vol. 97, pp. 151–163, Jan. 2019, doi: 10.1016/j.autcon.2018.10.021.

[14] Q. Chen, B. García de Soto, and B. T. Adey, “Construction automation: Research areas, industry concerns and suggestions for advancement,” *Automation in Construction*, vol. 94, pp. 22–38, Oct. 2018, doi: 10.1016/j.autcon.2018.05.028.

[15] M. Abushwereb, “Framework for automated manufacturing-centric BIM for light wood frame buildings,” University of Alberta, 2019.

[16] S. An, P. Martinez, M. Al-Hussein, and R. Ahmad, “BIM-based decision support system for automated manufacturability check of wood frame assemblies,” *Automation in Construction*, vol. 111, p. 103065, Mar. 2020, doi: https://doi.org/10.1016/j.autcon.2019.103065.

[17] S. An, “A design support system to determine the machine eligibility for manufacturing frame assemblies,” University of Alberta, 2019.

[18] N. Jazdi, “Cyber physical systems in the context of Industry 4.0,” in *2014 IEEE International Conference on Automation, Quality and Testing, Robotics*, May 2014, pp. 1–4, doi: 10.1109/AQTR.2014.6857843.

[19] X. Xu, L. Wang, and S. T. Newman, “Computer-aided process planning – A critical review of recent developments and future trends,” *International Journal of Computer Integrated Manufacturing*, vol. 24, no. 1, pp. 1–31, Jan. 2011, doi: 10.1080/0951192X.2010.518632.

[20] A. Schubert, “Scientometrics: The Research Field and its Journal,” 2001, pp. 179–195.

[21] P. Martinez, M. Al-Hussein, and R. Ahmad, “A scientometric analysis and critical review of computer vision applications for construction,” *Automation in Construction*, vol. 107, p. 102947, Nov. 2019, doi: https://doi.org/10.1016/j.autcon.2019.102947.

[22] Z. A. Shukra and Y. Zhou, “Holistic green BIM: a scientometrics and mixed review,” *Engineering, Construction and Architectural Management*, vol. 28, no. 9, pp. 2273–2299, Nov. 2021, doi: 10.1108/ECAM-05-2020-0377.

[23] P.-S. Lee, J. D. West, and B. Howe, “Viziometrics: Analyzing Visual Information in the Scientific Literature,” *IEEE Transactions on Big Data*, vol. 4, no. 1, pp. 117–129, Mar. 2018, doi: 10.1109/TBDATA.2017.2689038.

[24] N. J. van Eck and L. Waltman, “CitNetExplorer: A new software tool for analyzing and visualizing citation networks,” *Journal of Informetrics*, vol. 8, no. 4, pp. 802–823, Oct. 2014, doi: 10.1016/j.joi.2014.07.006.

[25] P. Mongeon and A. Paul-Hus, “The journal coverage of Web of Science and Scopus: a comparative analysis,” *Scientometrics*, vol. 106, no. 1, pp. 213–228, Jan. 2016, doi: 10.1007/s11192-015-1765-5.

[26] A. Abrizah, A. N. Zainab, K. Kiran, and R. G. Raj, “LIS journals scientific impact and subject categorization: a comparison between Web of Science and Scopus,” *Scientometrics*, vol. 94, no. 2, pp. 721–740, Feb. 2013, doi: 10.1007/s11192-012-0813-7.

[27] L. Leydesdorff and S. Milojević, “Scientometrics,” Aug. 2012, doi: https://doi.org/10.48550/arXiv.1208.4566.

[28] G. M. Dobrov, R. H. Randolph, and W. D. Rauch, “New options for team research via international computer networks,” *Scientometrics*, vol. 1, no. 5–6, pp. 387–404, Aug. 1979, doi: 10.1007/BF02016658.

[29] Z. M. Mulchenko, Y. V. Granovsky, and A. B. Strakhov, “On scientometrical characteristics on information activities of leading scientists,” *Scientometrics*, vol. 1, no. 4, pp. 307–325, May 1979, doi: 10.1007/BF02019303.

[30] B. Y. Brusilovsky, “Partial and system forecasts in scientometrics,” *Technological Forecasting and Social Change*, vol. 12, no. 2–3, pp. 193–200, Aug. 1978, doi: 10.1016/0040-1625(78)90055-0.

[31] Liu, Lu, and Peh, “A Review and Scientometric Analysis of Global Building Information Modeling (BIM) Research in the Architecture, Engineering and Construction (AEC) Industry,” *Buildings*, vol. 9, no. 10, p. 210, Sep. 2019, doi: 10.3390/buildings9100210.

[32] Q. He, G. Wang, L. Luo, Q. Shi, J. Xie, and X. Meng, “Mapping the managerial areas of Building Information Modeling (BIM) using scientometric analysis,” *International Journal of Project Management*, vol. 35, no. 4, pp. 670–685, May 2017, doi: 10.1016/j.ijproman.2016.08.001.

[33] A. Vaseashta, “Advanced sciences convergence based methods for surveillance of emerging trends in science, technology, and intelligence,” *Foresight*, vol. 16, no. 1, pp. 17–36, Mar. 2014, doi: 10.1108/FS-10-2012-0074.

[34] K. Jones, "Mass Timber Construction Starting to Take Root in U.S.," *constructionconnect*, Feb. 15, 2017. https://www.constructconnect.com/blog/mass-timber-construction-starting-take-root-u-s.

[35] D. Barber, "Fire Safety of Mass timber Buildings with CLT in USA," *Wood and Fiber Science*, vol. 50, no. Special, pp. 83–95, Aug. 2018, doi: 10.22382/wfs-2018-042.

[36] N. J. van Eck and L. Waltman, "Citation-based clustering of publications using CitNetExplorer and VOSviewer," *Scientometrics*, vol. 111, no. 2, pp. 1053–1070, May 2017, doi: 10.1007/s11192-017-2300-7.

[37] N. J. van Eck and L. Waltman, "Software survey: VOSviewer, a computer program for bibliometric mapping.," *Scientometrics*, vol. 84, no. 2, pp. 523–538, Aug. 2010, doi: 10.1007/s11192-009-0146-3.

[38] N. J. van Eck and L. Waltman, "Visualizing Bibliometric Networks," in *Measuring Scholarly Impact*, Cham: Springer International Publishing, 2014, pp. 285–320.

[39] A. Perianes-Rodriguez, L. Waltman, and N. J. van Eck, "Constructing bibliometric networks: A comparison between full and fractional counting," *Journal of Informetrics*, vol. 10, no. 4, pp. 1178–1195, Nov. 2016, doi: 10.1016/j.joi.2016.10.006.

[40] T. Vilutiene, D. Kalibatiene, M. R. Hosseini, E. Pellicer, and E. K. Zavadskas, "Building Information Modeling (BIM) for Structural Engineering: A Bibliometric Analysis of the Literature," *Advances in Civil Engineering*, vol. 2019, pp. 1–19, Aug. 2019, doi: 10.1155/2019/5290690.

[41] M. Oraee, M. R. Hosseini, E. Papadonikolaki, R. Palliyaguru, and M. Arashpour, "Collaboration in BIM-based construction networks: A bibliometric-qualitative literature review," *International Journal of Project Management*, vol. 35, no. 7, pp. 1288–1301, Oct. 2017, doi: 10.1016/j.ijproman.2017.07.001.

[42] N. J. van Eck and L. Waltman, "VOSviewer Manual version 1.6.18," Jan. 24, 2022. https://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.18.pdf (accessed Apr. 21, 2022).

[43] C. Chaomei, *CiteSpace: A Practical Guide for Mapping Scientific Literature*. 2016.

[44] J. Kleinberg, "Bursty and Hierarchical Structure in Streams *," *Data Mining and Knowledge Discovery*, vol. 7, pp. 373–397, 2003, doi: 10.1023/A:1024940629314.

[45] C. Chen, *The CiteSpace Manual*, vol. 1, no. 3. College of Computing and Informatics, Drexel University, 2014.

[46] M. E. J. Newman, "Modularity and community structure in networks," *Proceedings of the National Academy of Sciences*, vol. 103, no. 23, pp. 8577–8582, Jun. 2006, doi: 10.1073/pnas.0601602103.

[47] C. Chen, F. Ibekwe-SanJuan, and J. Hou, "The structure and dynamics of cocitation clusters: A multiple-perspective cocitation analysis," *Journal of the American Society for Information Science and Technology*, vol. 61, no. 7, pp. 1386–1409, Mar. 2010, doi: 10.1002/asi.21309.

[48] C. Chen, "The centrality of pivotal points in the evolution of scientific networks," in *Proceedings of the 10th international conference on Intelligent user interfaces*, Jan. 2005, pp. 98–105, doi: 10.1145/1040830.1040859.

[49] R. Brandner, G. Flatscher, A. Ringhofer, G. Schickhofer, and A. Thiel, "Cross laminated timber (CLT): overview and development," *European Journal of Wood and Wood Products*, vol. 74, no. 3, pp. 331–351, May 2016, doi: 10.1007/s00107-015-0999-5.

[50] L. C. Freeman, "A Set of Measures of Centrality Based on Betweenness," *Sociometry*, vol. 40, no. 1, p. 35, Mar. 1977, doi: 10.2307/3033543.

[51] R. McClung, H. Ge, J. Straube, and J. Wang, "Hygrothermal performance of cross-laminated

timber wall assemblies with built-in moisture: field measurements and simulations," *Building and Environment*, vol. 71, pp. 95–110, Jan. 2014, doi: 10.1016/j.buildenv.2013.09.008.

[52] M. H. Ramage *et al.*, "The wood from the trees: The use of timber in construction," *Renewable and Sustainable Energy Reviews*, vol. 68, pp. 333–359, Feb. 2017, doi: 10.1016/j.rser.2016.09.107.

[53] T. Ehrhart and R. Brandner, "Rolling shear: Test configurations and properties of some European soft- and hardwood species," *Engineering Structures*, vol. 172, pp. 554–572, Oct. 2018, doi: 10.1016/j.engstruct.2018.05.118.

[54] O. Espinoza, V. Rodriguez Trujillo, M. F. Laguarda Mallo, and U. Buehlmann, "Cross-Laminated Timber: Status and Research Needs in Europe," *BioResources*, vol. 11, pp. 281–295, 2016, Accessed: May 02, 2022. [Online]. Available: https://ojs.cnr.ncsu.edu/index.php/BioRes/article/view/BioRes_11_1_281_Espinoza_Cross_Laminated_Timber_Europe.

[55] I. Gavric, M. Fragiacomo, and A. Ceccotti, "Cyclic behaviour of typical metal connectors for cross-laminated (CLT) structures," *Materials and Structures*, vol. 48, no. 6, pp. 1841–1857, Jun. 2015, doi: 10.1617/s11527-014-0278-7.

[56] K. S. Sikora, D. O. McPolin, and A. M. Harte, "Effects of the thickness of cross-laminated timber (CLT) panels made from Irish Sitka spruce on mechanical performance in bending and shear," *Construction and Building Materials*, vol. 116, pp. 141–150, Jul. 2016, doi: 10.1016/j.conbuildmat.2016.04.145.

[57] L. Wang and H. Ge, "Hygrothermal performance of cross-laminated timber wall assemblies: A stochastic approach," *Building and Environment*, vol. 97, pp. 11–25, Feb. 2016, doi: 10.1016/j.buildenv.2015.11.034.

[58] I. Gavric, M. Fragiacomo, and A. Ceccotti, "Cyclic Behavior of CLT Wall Systems: Experimental Tests and Analytical Prediction Models," *Journal of Structural Engineering*, vol. 141, no. 11, p. 04015034, Nov. 2015, doi: 10.1061/(ASCE)ST.1943-541X.0001246.

[59] S. Aicher, M. Hirsch, and Z. Christian, "Hybrid cross-laminated timber plates with beech wood cross-layers," *Construction and Building Materials*, vol. 124, pp. 1007–1018, Oct. 2016, doi: 10.1016/j.conbuildmat.2016.08.051.

[60] F. Asdrubali, B. Ferracuti, L. Lombardi, C. Guattari, L. Evangelisti, and G. Grazieschi, "A review of structural, thermo-physical, acoustical, and environmental properties of wooden materials for building applications," *Building and Environment*, vol. 114, pp. 307–332, Mar. 2017, doi: 10.1016/j.buildenv.2016.12.033.

[61] H. Mpidi Bita and T. Tannert, "Disproportionate collapse prevention analysis for a mid-rise flat-plate cross-laminated timber building," *Engineering Structures*, vol. 178, pp. 460–471, Jan. 2019, doi: 10.1016/j.engstruct.2018.10.048.

[62] Y. Liao *et al.*, "Feasibility of manufacturing cross-laminated timber using fast-grown small diameter eucalyptus lumbers," *Construction and Building Materials*, vol. 132, pp. 508–515, Feb. 2017, doi: 10.1016/j.conbuildmat.2016.12.027.

[63] A. Hassanieh, H. R. Valipour, and M. A. Bradford, "Experimental and numerical investigation of short-term behaviour of CLT-steel composite beams," *Engineering Structures*, vol. 144, pp. 43–57, Aug. 2017, doi: 10.1016/j.engstruct.2017.04.052.

[64] A. Ceccotti, C. Sandhaas, M. Okabe, M. Yasumura, C. Minowa, and N. Kawai, "SOFIE project - 3D shaking table test on a seven-storey full-scale cross-laminated timber building," *Earthquake Engineering & Structural Dynamics*, vol. 42, no. 13, pp. 2003–2021, Oct. 2013, doi: 10.1002/eqe.2309.

[65] M. Izzi, D. Casagrande, S. Bezzi, D. Pasca, M. Follesa, and R. Tomasi, "Seismic behaviour of Cross-Laminated Timber structures: A state-of-the-art review," *Engineering Structures*, vol. 170, pp. 42–52, Sep. 2018, doi: 10.1016/j.engstruct.2018.05.060.

[66] I. Shahnewaz, T. Tannert, M. Shahria Alam, and M. Popovski, “In-Plane Stiffness of Cross-Laminated Timber Panels with Openings,” *Structural Engineering International*, vol. 27, no. 2, pp. 217–223, May 2017, doi: 10.2749/101686617X14881932436131.

[67] S. Gagnon and E. Karacabeyli, “Status of cross-laminated timber construction in North-America,” in *Structures and Architecture: Concepts, Applications and Challenges*, Taylor & Francis Group, London, 2013, pp. 66–73.

[68] M. O. Amini, J. W. van de Lindt, D. Rammer, S. Pei, P. Line, and M. Popovski, “Systematic experimental investigation to support the development of seismic performance factors for cross laminated timber shear wall systems,” *Engineering Structures*, vol. 172, pp. 392–404, Oct. 2018, doi: 10.1016/j.engstruct.2018.06.021.

[69] E. L. Schmidt, M. Riggio, A. R. Barbosa, and I. Mugabo, “Environmental response of a CLT floor panel: Lessons for moisture management and monitoring of mass timber buildings,” *Building and Environment*, vol. 148, pp. 609–622, Jan. 2019, doi: 10.1016/j.buildenv.2018.11.038.

[70] M. He, X. Sun, and Z. Li, “Bending and compressive properties of cross-laminated timber (CLT) panels made from Canadian hemlock,” *Construction and Building Materials*, vol. 185, pp. 175–183, Oct. 2018, doi: 10.1016/j.conbuildmat.2018.07.072.

[71] F. Pierobon, M. Huang, K. Simonen, and I. Ganguly, “Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA based comparative case study in the U.S. Pacific Northwest,” *Journal of Building Engineering*, vol. 26, p. 100862, Nov. 2019, doi: 10.1016/j.jobe.2019.100862.

[72] F. Morandi, S. De Cesaris, M. Garai, and L. Barbaresi, “Measurement of flanking transmission for the characterisation and classification of cross laminated timber junctions,” *Applied Acoustics*, vol. 141, pp. 213–222, Dec. 2018, doi: 10.1016/j.apacoust.2018.07.009.

[73] K. Jones, J. Stegemann, J. Sykes, and P. Winslow, “Adoption of unconventional approaches in construction: The case of cross-laminated timber,” *Construction and Building Materials*, vol. 125, pp. 690–702, Oct. 2016, doi: 10.1016/j.conbuildmat.2016.08.088.

[74] P. Crespell and S. Gagnon, *Cross laminated timber: a primer*, Special Edition, 52. FPInnovations, 2010.

[75] M. Popovski, J. Schneider, and M. Schweinsteiger, “LATERAL LOAD RESISTANCE OF CROSS-LAMINATED WOOD PANELS,” in *World Conference in Timber Engineering*, Jun. 2010, p. 24.

[76] A. Polastri, M. Izzi, L. Pozza, C. Loss, and I. Smith, “Seismic analysis of multi-storey timber buildings braced with a CLT core and perimeter shear-walls,” *Bulletin of Earthquake Engineering*, vol. 17, no. 2, pp. 1009–1028, Feb. 2019, doi: 10.1007/s10518-018-0467-9.

[77] Y. Oktavianus, K. S. Kristombu Baduge, K. Orlowski, and P. Mendis, “Structural behaviour of prefabricated load bearing braced composite timber wall system,” *Engineering Structures*, vol. 176, pp. 555–568, Dec. 2018, doi: 10.1016/j.engstruct.2018.09.037.

[78] E. Gasparri, A. Lucchini, G. Mantegazza, and E. S. Mazzucchelli, “Construction management for tall CLT buildings: From partial to total prefabrication of façade elements,” *Wood Material Science & Engineering*, vol. 10, no. 3, pp. 256–275, Jul. 2015, doi: 10.1080/17480272.2015.1075589.

[79] S.-J. Pang and G. Y. Jeong, “Effects of combinations of lamina grade and thickness, and span-to-depth ratios on bending properties of cross-laminated timber (CLT) floor,” *Construction and Building Materials*, vol. 222, pp. 142–151, Oct. 2019, doi: 10.1016/j.conbuildmat.2019.06.012.

[80] S.-J. Pang and G. Y. Jeong, “Load sharing and weakest lamina effects on the compressive resistance of cross-laminated timber under in-plane loading,” *Journal of Wood Science*, vol. 64, no. 5, pp. 538–550, Oct. 2018, doi: 10.1007/s10086-018-1741-9.

[81] D. M. Fitzgerald, "Cross-Laminated Timber Shear Walls with Toe-Screwed and Slip-Friction Connections," Oregon State University, Oregon, 2019.

[82] J. S. Damtoft, J. Lukasik, D. Herfort, D. Sorrentino, and E. M. Gartner, "Sustainable development and climate change initiatives," *Cement and Concrete Research*, vol. 38, no. 2, pp. 115–127, Feb. 2008, doi: 10.1016/j.cemconres.2007.09.008.

[83] R. N. Passarelli and M. Koshihara, "CLT panels in Japan from cradle to construction site gate: global warming potential and freight costs impact of three supply options," *International Wood Products Journal*, vol. 8, no. 2, pp. 127–136, Apr. 2017, doi: 10.1080/20426445.2017.1317471.

[84] A. Ceccotti, "New Technologies for Construction of Medium-Rise Buildings in Seismic Regions: The XLAM Case," *Structural Engineering International*, vol. 18, no. 2, pp. 156–165, May 2008, doi: 10.2749/101686608784218680.

[85] T. Connolly, C. Loss, A. Iqbal, and T. Tannert, "Feasibility Study of Mass-Timber Cores for the UBC Tall Wood Building," *Buildings*, vol. 8, no. 8, p. 98, Aug. 2018, doi: 10.3390/buildings8080098.

[86] C. J. Turner, J. Oyekan, L. Stergioulas, and D. Griffin, "Utilizing Industry 4.0 on the Construction Site: Challenges and Opportunities," *IEEE Transactions on Industrial Informatics*, vol. 17, no. 2, pp. 746–756, Feb. 2021, doi: 10.1109/TII.2020.3002197.

[87] F. Bianconi, M. Filippucci, and A. Buffi, "Automated design and modeling for mass-customized housing. A web-based design space catalog for timber structures," *Automation in Construction*, vol. 103, pp. 13–25, Jul. 2019, doi: 10.1016/j.autcon.2019.03.002.

[88] M. Colella and G. Fallacara, "Towards a 4.0 Mass Customized Wooden Housing in the Mediterranean Area: The Ecodomus Project," 2019, pp. 1201–1228.

[89] A. Abbas, Z. U. Din, and R. Farooqui, "Integration of BIM in Construction Management Education: An Overview of Pakistani Engineering Universities," *Procedia Engineering*, vol. 145, pp. 151–157, 2016, doi: 10.1016/j.proeng.2016.04.034.

[90] G. Pasetti Monizza, C. Bendetti, and D. T. Matt, "Parametric and Generative Design techniques in mass-production environments as effective enablers of Industry 4.0 approaches in the Building Industry," *Automation in Construction*, vol. 92, pp. 270–285, Aug. 2018, doi: 10.1016/j.autcon.2018.02.027.

[91] E. Rauch, P. Dallasega, and D. T. Matt, "Complexity reduction in engineer-to-order industry through real-time capable production planning and control," *Production Engineering*, vol. 12, no. 3–4, pp. 341–352, Jun. 2018, doi: 10.1007/s11740-018-0809-0.

[92] P. Dallasega, E. Rauch, and C. Linder, "Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review," *Computers in Industry*, vol. 99, pp. 205–225, Aug. 2018, doi: 10.1016/j.compind.2018.03.039.

[93] T. D. Oesterreich and F. Teuteberg, "Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry," *Computers in Industry*, vol. 83, pp. 121–139, Dec. 2016, doi: 10.1016/j.compind.2016.09.006.

[94] A. Sawhney, M. Riley, and J. Irizarry, *Construction 4.0 An Innovation Platform for the Built Environment*, vol. 1st Edition. 2020.

[95] R. Woodhead, P. Stephenson, and D. Morrey, "Digital construction: From point solutions to IoT ecosystem," *Automation in Construction*, vol. 93, pp. 35–46, Sep. 2018, doi: 10.1016/j.autcon.2018.05.004.

[96] Y. Al-Saeed, D. J. Edwards, and S. Scaysbrook, "Automating construction manufacturing procedures using BIM digital objects (BDOs)," *Construction Innovation*, vol. 20, no. 3, pp. 345–377, Feb. 2020, doi: 10.1108/CI-12-2019-0141.

[97] C. Z. Li *et al.*, "Integrating RFID and BIM technologies for mitigating risks and improving schedule performance of prefabricated house construction," *Journal of Cleaner Production*, vol. 165, pp. 1048–1062, Nov. 2017, doi: 10.1016/j.jclepro.2017.07.156.

[98] S. Shirowzhan, S. M. E. Sepasgozar, D. J. Edwards, H. Li, and C. Wang, "BIM compatibility and its differentiation with interoperability challenges as an innovation factor," *Automation in Construction*, vol. 112, p. 103086, Apr. 2020, doi: 10.1016/j.autcon.2020.103086.

[99] R. Bortolini, C. T. Formoso, and D. D. Viana, "Site logistics planning and control for engineer-to-order prefabricated building systems using BIM 4D modeling," *Automation in Construction*, vol. 98, pp. 248–264, Feb. 2019, doi: 10.1016/j.autcon.2018.11.031.

[100] R. A. Buswell, W. R. Leal de Silva, S. Z. Jones, and J. Dirrenberger, "3D printing using concrete extrusion: A roadmap for research," *Cement and Concrete Research*, vol. 112, pp. 37–49, Oct. 2018, doi: 10.1016/j.cemconres.2018.05.006.

[101] J. Li, D. Greenwood, and M. Kassem, "Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases," *Automation in Construction*, vol. 102, pp. 288–307, Jun. 2019, doi: 10.1016/j.autcon.2019.02.005.

[102] R. M. Foster and M. H. Ramage, "Briefing: Super tall timber – Oakwood Tower," *Proceedings of the Institution of Civil Engineers - Construction Materials*, vol. 170, no. 3, pp. 118–122, Jun. 2017, doi: 10.1680/jcoma.16.00034.

[103] M. Kosacka-Olejnik and R. Pitakaso, "Industry 4.0: state of the art and research implications," *Logforum*, vol. 15, no. 4, pp. 478–485, Dec. 2019, doi: 10.17270/J.LOG.2019.363.

[104] C. Loss, S. Rossi, and T. Tannert, "In-Plane Stiffness of Hybrid Steel–Cross-Laminated Timber Floor Diaphragms," *Journal of Structural Engineering*, vol. 144, no. 8, p. 04018128, Aug. 2018, doi: 10.1061/(ASCE)ST.1943-541X.0002105.

[105] P. Mayencourt and C. Mueller, "Structural Optimization of Cross-laminated Timber Panels in One-way Bending," *Structures*, vol. 18, pp. 48–59, Apr. 2019, doi: 10.1016/j.istruc.2018.12.009.

[106] K. Orlowski, "Verified and validated design curves and strength reduction factors for post-tensioned composite steel-timber stiffened wall systems," *Engineering Structures*, vol. 204, p. 110053, Feb. 2020, doi: 10.1016/j.engstruct.2019.110053.

[107] S. Ghafoor and R. H. Crawford, "Comparative study of the life cycle embodied greenhouse gas emissions of panelised prefabricated residential walling systems in Australia," *Proceedings of the International Conference of Architectural Science Association*, vol. 2020-Novem, pp. 256–265, 2020.

[108] T. Østnor, S. Faanes, and O. Lædre, "Laminated Timber Versus on-Site Cast Concrete: A Comparative Study," Jul. 2018, pp. 1302–1312, doi: 10.24928/2018/0313.

[109] S. Bechert, L. Aldinger, D. Wood, J. Knippers, and A. Menges, "Urbach Tower: Integrative structural design of a lightweight structure made of self-shaped curved cross-laminated timber," *Structures*, vol. 33, pp. 3667–3681, Oct. 2021, doi: 10.1016/j.istruc.2021.06.073.

[110] J. Jamnitzky and A. Deák, "TUM-Campus im Olympiapark München," *Bautechnik*, vol. 96, no. 11, pp. 855–862, Nov. 2019, doi: 10.1002/bate.201900081.

[111] E. Gasparri and M. Aitchison, "Unitised timber envelopes. A novel approach to the design of prefabricated mass timber envelopes for multi-storey buildings," *Journal of Building Engineering*, vol. 26, p. 100898, Nov. 2019, doi: 10.1016/j.jobe.2019.100898.

[112] J. Gamerro, J. F. Bocquet, and Y. Weinand, "Experimental investigations on the load-carrying capacity of digitally produced wood-wood connections," *Engineering Structures*, vol. 213, p. 110576, Jun. 2020, doi: 10.1016/j.engstruct.2020.110576.

[113] A. Ahmadian Fard Fini, M. Maghrebi, P. J. Forsythe, and T. S. Waller, "Using existing site surveillance cameras to automatically measure the installation speed in prefabricated timber

construction," *Engineering, Construction and Architectural Management*, vol. 29, no. 2, pp. 573–600, Mar. 2022, doi: 10.1108/ECAM-04-2020-0281.

[114] A. Jalali Yazdi, A. Ahmadian Fard Fini, and P. Forsythe, "Mass-customisation of cross-laminated timber wall systems at early design stages," *Automation in Construction*, vol. 132, p. 103938, Dec. 2021, doi: 10.1016/j.autcon.2021.103938.

[115] G. Joyce and A. Pelosi, "Robotic Connections for CLT Panels," *RE: Anthropocene, Design in the Age of Humans - Proceedings of the 25th International Conference on Computer-Aided Architectural Design Research in Asia, CAADRIA 2020*, vol. 2, pp. 405–414, 2020.

[116] N. Früh, A. Amorth, and T. Wieland, "Holzbau-Formen für Stuttgart 21," *Bautechnik*, vol. 95, no. 7, pp. 505–511, Jul. 2018, doi: 10.1002/bate.201800042.

[117] T. Gollwitzer, A. Amorth, and D. Zausinger, "Synagoge Regensburg – eine Schale aus zweiachsig gekrümmtem Brettsperrholz," *Bautechnik*, vol. 96, no. 11, pp. 873–879, Nov. 2019, doi: 10.1002/bate.201900070.

[118] G. Poulden, "Buildings and Climate Change: Summary for Decision Makers," 2009. [Online]. Available: https://europa.eu/capacity4dev/unep/documents/buildings-and-climate-change-summary-decision-makers.

[119] P. D. Kremer and M. A. Symmons, "Mass timber construction as an alternative to concrete and steel in the Australia building industry: a PESTEL evaluation of the potential," *International Wood Products Journal*, vol. 6, no. 3, pp. 138–147, Aug. 2015, doi: 10.1179/2042645315Y.0000000010.

[120] J. Fraser, "Knock on (Engineered) Wood: Pathways to Increased Deployment of Cross-Laminated Timber," Lund University, 2017.

[121] H. Li, B. J. Wang, P. Wei, and L. Wang, "Cross-laminated Timber (CLT) in China: A State-of-the-Art," *Journal of Bioresources and Bioproducts*, vol. 4, no. 1, pp. 22–30, 2019, doi: https://doi.org/10.21967/jbb.v4i1.190.

[122] C. Robeller, M. Konakovic, M. Dedijer, M. Pauly, and Y. Weinand, "A Double-Layered Timber Plate Shell Computational," *Advances in Architectural Geometry*, vol. 5, pp. 104–122, 2016, doi: 10.3218/3778-4.

[123] C. Robeller and Y. Weinand, "A 3D cutting method for integral 1DOF multiple-tab-and-slot joints for timber plates, using 5-axis CNC cutting technology," *World Conference on Timber Engineering*, pp. 2576–2584, 2016.

[124] O. Ayari, A. Bouali, and P. J. Méausoone, "Cutting forces and accuracy characterization during wood machining with serial robots," *European Journal of Wood and Wood Products*, vol. 78, no. 4, pp. 767–775, 2020, doi: https://doi.org/10.1007/s00107-020-01539-4.

[125] S. Landscheidt, M. Kans, and M. Winroth, "Opportunities for Robotic Automation in Wood Product Industries: The Supplier and System Integrators' Perspective," *Procedia Manufacturing*, vol. 11, no. June, pp. 233–240, 2017, doi: 10.1016/j.promfg.2017.07.231.

[126] A. Klimchik, A. Ambiehl, S. Garnier, B. Furet, and A. Pashkevich, "Efficiency evaluation of robots in machining applications using industrial performance measure," *Robotics and Computer-Integrated Manufacturing*, vol. 48, no. October 2015, pp. 12–29, 2017, doi: 10.1016/j.rcim.2016.12.005.

[127] Alfredo Aguilera, "Monitoring Surface Quality on Molding and Sawing Processes for Solid Wood and Wood Panels," in *Wood Machining*, ISTE Ltd and John Wiley & Sons, Inc, 2011, pp. 159–211.

[128] A. A. Krimpenis, N. A. Fountas, T. Mantziouras, and N. M. Vaxevanidis, "Optimizing CNC wood milling operations with the use of genetic algorithms on CAM software," *Wood Material Science and Engineering*, vol. 11, no. 2, pp. 102–115, 2016, doi: 10.1080/17480272.2014.961959.

[129] S. An, P. Martinez, R. Ahmad, and M. Al-Hussein, "Ontology-Based Knowledge Modeling for Frame Assemblies Manufacturing," in *Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC 2019*, May 2019, no. Isarc, pp. 709–715, doi: 10.22260/ISARC2019/0095.

[130] P. Martinez, R. Ahmad, and M. Al-Hussein, "Real-time visual detection and correction of automatic screw operations in dimpled light-gauge steel framing with pre-drilled pilot holes," *Procedia Manufacturing*, vol. 34, pp. 798–803, 2019, doi: 10.1016/j.promfg.2019.06.204.

[131] P. Martinez, M. Livojevic, P. Jajal, D. R. Aldrich, M. Al-Hussein, and R. Ahmad, "Simulation-Driven Design of Wood Framing Support Systems for Off-Site Construction Machinery," *Journal of Construction Engineering and Management*, vol. 146, no. 7, p. 04020075, Jul. 2020, doi: 10.1061/(ASCE)CO.1943-7862.0001853.

[132] A. Nicolescu, M. Ivan, and C. Coman, "Virtual prototyping and programming of a robotic manufacturing cell for wood machining," vol. 13, no. 4, pp. 203–210, 2018.

[133] H. J. Wagner, M. Alvarez, O. Kyjanek, Z. Bhiri, M. Buck, and A. Menges, "Flexible and transportable robotic timber construction platform – TIM," *Automation in Construction*, vol. 120, no. February, p. 103400, 2020, doi: 10.1016/j.autcon.2020.103400.

[134] T. Linner *et al.*, "A technology management system for the development of single-task construction robots," *Construction Innovation*, vol. 20, no. 1, pp. 96–111, 2020, doi: 10.1108/CI-06-2019-0053.

[135] R. Vanova, P. Stompf, J. Stefko, and J. Stefkova, "Environmental Impact of a Mass Timber Building—A Case Study," *Forests*, vol. 12, no. 11, p. 1571, Nov. 2021, doi: 10.3390/f12111571.

[136] J. W. G. V. De Kuilen, A. Ceccotti, Z. Xia, and M. He, "Very Tall Wooden Buildings with Cross Laminated Timber," *Procedia Engineering*, vol. 14, pp. 1621–1628, 2011, doi: 10.1016/j.proeng.2011.07.204.

[137] T. Tannert *et al.*, "SEISMIC DESIGN OF CROSS-LAMINATED TIMBER BUILDINGS," *Wood and Fiber Science*, vol. 50, no. Special, pp. 3–26, Aug. 2018, doi: 10.22382/wfs-2018-037.

[138] M. Pérez and M. Fuente, "Acoustic design through predictive methods in Cross Laminated Timber (CLT) panel structures for buildings," 2013. [Online]. Available: https://www.researchgate.net/publication/260904195.

[139] M. Alvarez *et al.*, "The Buga Wood Pavilion," *Arcadia*, vol. 19, 2019, Accessed: Jan. 31, 2022. [Online]. Available: http://papers.cumincad.org/cgi-bin/works/paper/acadia19_490.

[140] S. Bechert, D. Sonntag, L. Aldinger, and J. Knippers, "Integrative structural design and engineering methods for segmented timber shells - BUGA Wood Pavilion," *Structures*, vol. 34, pp. 4814–4833, Dec. 2021, doi: 10.1016/j.istruc.2021.10.032.

[141] N. K. Jain and V. K. Jain, "Computer Aided Process Planning for Agile Manufacturing Environment," in *Agile Manufacturing: The 21st Century Competitive Strategy*, Elsevier, 2001, pp. 515–534.

[142] M. Darwish, "Residential construction manufacturing estimating framework: the case of lightweight timber framing," University of Alberta, 2020.

[143] R. Cui, J. Zhang, P. Feng, D. Yu, and Z. Wu, "A Path Planning Method for V-Shaped Robotic Cutting of Nomex Honeycomb by Straight Blade Tool," *IEEE Access*, vol. 8, pp. 162763–162774, 2020, doi: 10.1109/ACCESS.2020.3021121.

[144] F. Hähn and M. Weigold, "Hybrid compliance compensation for path accuracy enhancement in robot machining," *Production Engineering*, vol. 14, no. 4, pp. 425–433, Oct. 2020, doi: 10.1007/s11740-020-00976-7.

[145] L. Lu *et al.*, "Joint-smooth Toolpath Planning by Optimized Differential Vector for Robot

Surface Machining Considering the Tool Orientation Constraints," *IEEE/ASME Transactions on Mechatronics*, pp. 1–1, 2021, doi: 10.1109/TMECH.2021.3104477.

[146] D. Lyu, Q. Liu, H. Liu, and W. Zhao, "Dynamic error of CNC machine tools: a state-of-the-art review," *The International Journal of Advanced Manufacturing Technology*, vol. 106, no. 5–6, pp. 1869–1891, Jan. 2020, doi: 10.1007/s00170-019-04732-9.

[147] Y. SUN, J. JIA, J. XU, M. CHEN, and J. NIU, "Path, feedrate and trajectory planning for free-from surface machining: A state-of-the-art review," *Chinese Journal of Aeronautics*, Jul. 2021, doi: 10.1016/j.cja.2021.06.011.

[148] K. Latif, A. Adam, Y. Yusof, and A. Z. A. Kadir, "A review of G code, STEP, STEP-NC, and open architecture control technologies based embedded CNC systems," *The International Journal of Advanced Manufacturing Technology*, vol. 114, no. 9–10, pp. 2549–2566, Jun. 2021, doi: 10.1007/s00170-021-06741-z.

[149] M. Dhanda and S. Pande, "Adaptive Tool Path Planning Strategy for Freeform Surface Machining using Point Cloud," *Computer-Aided Design and Applications*, vol. 16, no. 2, pp. 289–307, Aug. 2018, doi: 10.14733/cadaps.2019.289-307.

[150] D. Song *et al.*, "Iso-parametric path-planning method of twin-tool milling for turbine blades," *The International Journal of Advanced Manufacturing Technology*, vol. 98, no. 9–12, pp. 3179–3189, Oct. 2018, doi: 10.1007/s00170-018-2461-4.

[151] F. Wulle, M. Richter, C. Hinze, and A. Verl, "Time-optimal Path Planning of Multi-axis CNC Processes Using Variability of Orientation," *Procedia CIRP*, vol. 96, pp. 324–329, 2021, doi: 10.1016/j.procir.2021.01.095.

[152] J. Ma, D. Song, Z. Jia, G. Hu, W. Su, and L. Si, "Tool-path planning with constraint of cutting force fluctuation for curved surface machining," *Precision Engineering*, vol. 51, pp. 614–624, Jan. 2018, doi: 10.1016/j.precisioneng.2017.11.002.

[153] H.-C. MÖHRING, T. STEHLE, and M. SCHNEIDER, "LIGHTWEIGHT MACHINE ENCLOSURES FOR DYNAMIC AND EFFICIENT PRODUCTION PROCESSES," *Journal of Machine Engineering*, vol. 19, no. 2, pp. 46–53, Jun. 2019, doi: 10.5604/01.3001.0013.2350.

[154] A. Petrovic, L. Lukic, S. Ivanovic, and A. Pavlovic, "Optimisation of tool path for wood machining on CNC machines," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 231, no. 1, pp. 72–87, Jan. 2017, doi: 10.1177/0954406216648715.

[155] A. Makris and I. Ntintakis, "Toolpath generation and optimization of machining of pine woodsurfaces," *Innovation in Forestry Industry and Engineering Design*, vol. 8, no. 1, pp. 37–46, 2019, [Online]. Available: https://www.researchgate.net/publication/328132182.

[156] G. Pinkowski, W. Szymański, and A. Krauss, "Milling quality of sweet cherry (Prunus avium L.) wood on a CNC woodworking machine," 2013.

[157] V. Novák, M. Rousek, and Z. Kopecký, "Assessment of Wood Surface Quality Obtained During High Speed Milling by Use of Non-Contact Method," *Drvna industrija*, vol. 62, no. 2, pp. 105–113, Jun. 2011, doi: 10.5552/drind.2011.1027.

[158] Prakash S, Palanikumar K, L. Mercy, and Nithyalakshmi S, "EVALUATION OF SURFACE ROUGHNESS PARAMETERS (Ra, Rz) IN DRILLING OF MDF COMPOSITE PANEL USING BOX-BEHNKEN EXPERIMENTAL DESIGN (BBD)," *.International Journal on Design and Manufacturing Technologies*, vol. 5, no. 1, pp. 52–62, 2011, Accessed: Feb. 03, 2022. [Online]. Available: https://www.proquest.com/docview/1765369723?pq-origsite=gscholar&fromopenview=true#.

[159] P. S. Ogun and M. R. Jackson, "Active vibration control and real-time cutter path modification in rotary wood planing," *Mechatronics*, vol. 46, pp. 21–31, Oct. 2017, doi: 10.1016/j.mechatronics.2017.06.007.

[160] S. Eschelbacher, J. Duntschew, and H.-C. Möhring, “Recognition of wood and wood-based materials during machining using acoustic emission,” in *Production at the leading edge of technology*, J. P. Wulfsberg, W. Hintze, and B.-A. Behrens, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2019, pp. 317–325.

[161] A. Atmosudiro, M. Keinert, A. Karim, A. Lechler, A. Verl, and A. Csizar, “Productivity Increase through Joint Space Path Planning for Robot Machining,” in *2014 European Modelling Symposium*, Oct. 2014, pp. 257–262, doi: 10.1109/EMS.2014.46.

[162] R. Bullock, “Least-Squares Circle Fit,” *Developmental Testbed Center*, pp. 1–3, 2017, Accessed: Apr. 06, 2022. [Online]. Available: https://dtcenter.org/sites/default/files/community-code/met/docs/write-ups/circle_fit.pdf.

[163] Z. Yao and S. K. Gupta, “Cutter path generation for 2.5D milling by combining multiple different cutter path patterns,” *International Journal of Production Research*, vol. 42, no. 11, pp. 2141–2161, Jun. 2004, doi: 10.1080/00207540310001652879.

[164] E. Martinez Villanueva, H. Mamledesai, P. Martinez, P. Poostchi, and R. Ahmad, “Design and simulation of an automated robotic machining cell for cross-laminated timber panels,” *Procedia CIRP*, vol. 100, pp. 175–180, 2021, doi: 10.1016/j.procir.2021.05.026.