

Parametric and Generative Design Techniques for Digitalization in Building Industry: the Case Study of Glued-Laminated-Timber Industry

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Abstract. According to Wortmann classification, the Building Industry (BI) can be defined as engineer-to-order (ETO) industry: the engineering-process starts only when an order is acquired. This definition implies that every final product (building) is almost unique, and processes cannot be easily standardized or automated. Because of this, BI is one of the less efficient industries today, mostly leaded by craftsmanship. In the last years, several improvements in process efficiency have been made focusing on manufacturing and installation processes only. In order to improve the efficiency of design and engineering processes as well, the scientific community agrees that the most fruitful strategy should be Front-End Design (FED). Nevertheless, effective techniques and tools are missing. This paper discusses outcomes of a research activity that aims at highlighting whether Parametric and Generative Design techniques allow reducing wastes of resources and improving the overall efficiency of the BI, by pushing the Digitalization of design and engineering processes of products. Focusing on the Glued-Laminated-Timber industry, authors will show how Parametric and Generative Design techniques can be introduced in a standard supply-chain system, highlighting potentials and criticism on the supply-chain system as a whole.

1. Introduction

According to ISTAT surveys [1], Building Industry (BI) is one of the less efficient industries in Italy and the productivity gap with other industries is growing faster. This gap is due to two main reasons. Firstly, BI can be defined as an engineer-to-order (ETO) industry following Wortmann classification [2]. Secondly, BI identifies different responsible figures for each process usually structured in a serial workflow. Serial workflow reduces the efficiency of information management by enhancing the propagation of errors because of fragmented information flow among the responsible figures.

Today, the challenge for BI is to reduce the productivity gap with other industries by reducing the wastes of resources and improving the overall efficiency of the supply-chain system [3] [4]. Improving the overall efficiency in BI may generate huge benefits: reduce social and economic costs, reduce the environmental footprint and enhance the quality of final products (buildings).

1.1. Parametric and generative design techniques

According to Jabi's definition [5], Parametric Design is "the processes based on algorithmic thinking that enables the expression of parameters and rules that, together, define, encode and clarify the relationship between design intent and design response". This relationship is expressed through a relationship between elements (components) that leads the manipulation and the generation of complex geometries and structures. Whether parametric algorithms use iteratively some components



in order to identify the best solution to a specific design intent within design boundaries (parameters and rules), the process may be defined as Generative Design technique.

Nowadays, computers aid the algorithmic thinking and scripts are the formal expression of design algorithms. Parametric and Generative Design techniques have been adopted with effective result for design automation, form-finding strategies and digital fabrication strategies [6] [7]. Nevertheless, due to a lack of automation in standard manufacturing processes, digital fabrication strategies are far from a broad application in the BI.

Parametric and Generative Design techniques may be considered Knowledge-Based Engineering (KBE) techniques, according to its definition [8]. Nevertheless they lack in common libraries and dictionaries which have to be defined on purpose time by time.

1.2. Glued-Laminated-Timber technology

Glued-Laminated Timber (also known as GLT or glulam) is the most ancient engineered wood product. Since from Leonardo da Vinci's studies until the official patent by Hetzer in 1905, the main purposes of this product are to enhance the mechanical performances and to increase the dimension limits of the raw material (wood). In order to fulfil these purposes, it is manufactured by bonding together selected timber elements (laminates) and reducing the natural defects of the raw material.

Focusing on the case study of the glued-laminated-timber industry, the research presented in this paper aims at highlighting whether Parametric and Generative design techniques allow reducing wastes of resources and improving the overall efficiency of the supply-chain system as a whole, by pushing the Digitalization of design and engineering processes of products. Authors will discuss possible improvements to an ordinary production system of GLT in order to fulfil the minimum requirements of automation in order to make effective parametric and generative design techniques.

2. Methods

Research activities have been planned through two main phases:

- The first phase develops a specific parametric and generative algorithm that can be applied on design and engineering process of GLT products. The algorithm will be stress-tested by designing and engineering some prototypes, which have to satisfy different customer's need randomly generated. This test has to highlight the robustness and the flexibility of the algorithms against different designed geometries or different structural designs.
- The second phase aims at testing benefits and criticisms of parametric and generative algorithm on an ordinary production system of GLT. The test is performed using the Value-Stream-Mapping (VSM) technique. In order to measure effects of parametric and generative algorithms, a comparison between two value-stream maps (one referred to an ordinary production system and one using parametric and generative algorithms) will be developed focusing on both process timing and resource commitment.

The research is currently going to develop the second phase. A first version of the algorithm has been programmed and authors concluded a first survey of an ordinary production system of GLT. Authors are going to conclude the value-stream map of the ordinary production system of GLT and to start activities aiming at defining the value-stream map of a production system using parametric and generative algorithms.

Referring to case studies of KBE [9] [10], the approach proposed is more similar to KBE applications in automotive or aeronautical industry than applications in building industry: usually aiming at facilitating early design activities of entire buildings instead of single elements or products.

2.1. The programmed algorithm

The programmed algorithm develops two specific design intents (Figure 1 shows the algorithm's strategy): reduce the usage of unneeded high-quality raw material in final products and facilitate the manufacturing process. These design intents will be developed independently from the designed geometry and the overall structural design. In order to fulfil the first design intent, the algorithm has been designed combining the possible optimizations offered by standards and codes (EN 14080, the

German standard DIN 1052 and the European structural code for timber structures - Eurocode 5) [11] [12] [13]. Once inputs have been defined, the algorithm performs two different analysis:

- a mechanical stress analysis (through FEM simulations) to define the section areas of final products that are more stressed in order to use high-quality raw material only where needed (Figure 2-3);
- a curvature analysis to identify manufacturing strategies that should prevent possible reductions of mechanical performances of products.

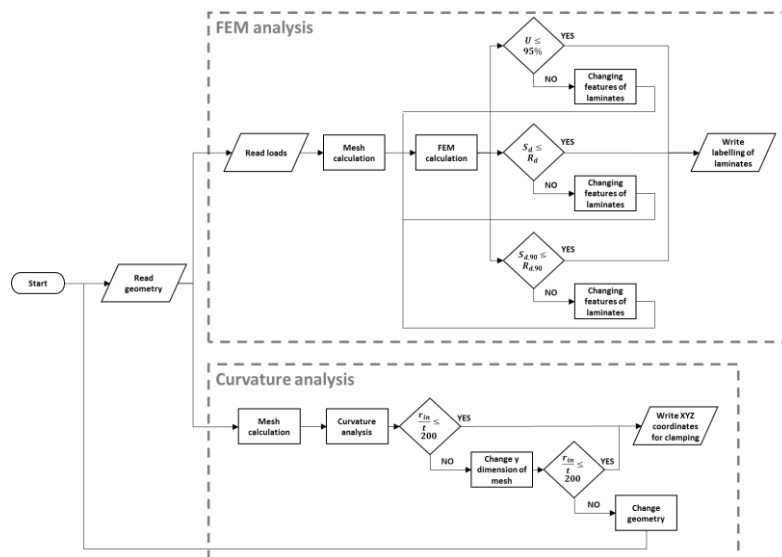


Figure 1. Preliminary flowchart of the designed strategy.

Whether optimizations are not performed the algorithm has to reduce mechanical performances of final products and iteratively change their geometry until the required performance is reached. For further details about the algorithm's strategy, readers may refer to previous publication by authors.

The outputs of the algorithm may be used for a cross-analysis with the ordinary supply-chain system of glued-laminated timber, highlighting benefits, criticism and possible improvements. The main intent of the authors during the discussion is to provide a case study, which may become a reference for transferring the adopted strategy to other building products.

3. Discussion

According to scientific literature [14] and to the first survey on a real production system, the production system of GLT is divided in five main stages:

- The process starts with a strength grading of sawn timber. Usually this is a machine-driven stage. It allows to grade timber elements by removing parts containing defects (such as large knots, irregular grains, etc.).
- After trimming out defects, according to the identified timber strength class, the required lamination length is obtained by finger jointing. This stage is machine-driven as well. At the end of these two stages selected laminates could be stored for a while for glue curing or, if allowed by a fast curing glue, they are sent to assembly area for the laying-up stages.
- Laminates strength for each layer are identified and manually selected for further stages. Just before starting the laying-up stages, regular laminates' thicknesses and depths are achieved using planers.
- Once laminates are covered by adhesive on selected faces, they are assembled and cramped together waiting for glue curing. Straight glued-laminated products are usually cramped using

automatic pressing machines. In case of complex geometries or curvatures, manual jigs are used for laying-up and cramping.

- Regular products' dimension are achieved using automatic or manual planers. At the end, after finishing products using coatings and paints, they are packed and labelled, ready for shipping.

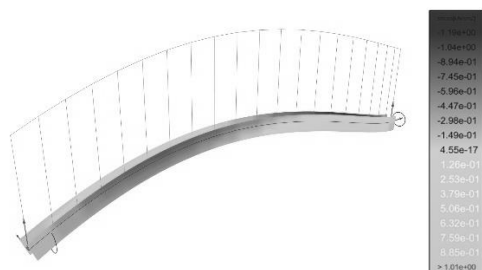


Figure 2. Example of FEM simulation of a double curved beam performed through the algorithm.

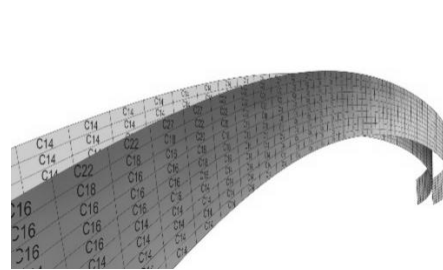


Figure 3. Labelling of laminates after FEM simulation.

The cross-analysis can be developed crossing the analysis performed by the programmed algorithm and manufacturing stages of the ordinary production system previously defined. From early evaluations, waiting for results from VSM analysis, authors identified some improvements of front-end activities of the supply-chain system such as design and engineering processes of GLT products. A uniform language (scripts) offered by parametric and generative algorithms avoids possible misunderstandings among responsible figures of design and engineering processes and enhance the efficiency of the overall communication management. Moreover, the automation of specific stages across design and engineering processes allows to overcome limitations in optimizations offered by the normative and to speeds up ordinary tasks as well as custom tasks in special commitments, such as the design and the engineering of double-curved GLT products.

Although parametric and generative algorithms can save 30% of high-quality raw material thanks to optimizations introduced across design and engineering processes, benefits on the manufacturing process of GLT are limited by lack of automation of specific stages across the production system. The strength grading and the finger jointing stages are arranged in a rigid serial workflow. This means that only homogeneous laminates can be manufactured. Parametric and generative outputs may become effective only whether machineries can manufacture inhomogeneous laminates. Companies could achieve this result without a huge effort. The sawn timber has to be arranged to provide different qualities of raw material just before the strength grading. This could be done by manually loading the strength-grading machinery or by adopting a machine that select the needed sawn timber. The strength-grading machine, interacting with the cutting machine and with the finger-jointing machine, has to acquire outputs from the algorithm in order to drive the length of each element across laminates and in order to request specific quality of raw material. Moreover, during laying-up and cramping stages, the curvature and the final geometry of products is achieved using manual jigs, this means that algorithm outputs may support operators setting-up jigs but this stage is still done manually. Whether companies would adopt an automatic pressing machine that can handle curvature in final products by a numerical control, the benefits of parametric and generative outputs could be stronger. Nevertheless, this kind of pressing machine is not available on the market nowadays: the installation would be a custom installation that needs huge investments.

4. Conclusions

Considering that results could be assumed only in a preliminary stage due to incomplete research phases and to the absence of a prototyping phase due to a lack of resources, it is possible to highlight that:

- Parametric and Generative Design techniques allow a strong improvement acquiring and handling design contents from responsible figures of design and engineering processes. This

strongly increase the efficiency of the value-chain in the front-end processes mainly thanks to a more efficient communication management due to a uniform language.

- These approaches make optimization of production system easier thanks to a front-loading of manufacturing strategies and concerns during design activities.
- In order to produce effective benefits on manufacturing processes, these approaches require a strong automation across the production system. Referring to the case study, authors would like to remark that the interaction between parametric and generative outputs and machine-driven manufacturing stages could be not so easily achieved. Whether custom machinery has to be adopted, return of investments might be not sustainable in a short term for companies.

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