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Parametric and Generative Design Techniques for Mass-Customization in Building Industry: a Case Study for Glued-Laminated Timber

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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. For this reason, the Building Industry is one of the less efficient industries today, and the productivity gap with other industries is growing faster. Since the 1940s, prefabrication and standardization of entire buildings or of complex components are effective strategies to push BI from an ETO industry towards an assembly-to-order industry (ATO). Although, prefabrication and standardization strategies provide effective solutions to improve process efficiency, they are not widespread adopted. The reason for this poor success can be identified in limits of customization that afflicts prefabricated and standardized products, which do not satisfy completely the needs usually delivered by customers. This paper presents a research activity aiming at enhancing Mass-Customization capabilities in the BI through Parametric and Generative design techniques in frontend activities of the value-chain system. Referring to a case study for Glued-Laminated Timber (GLT) products, a parametric algorithm has been programmed in order to satisfy two specific design intents: reducing the usage of unneeded high-quality raw material in final products and facilitating the manufacturing process of complex products, such as doubled-curved ones. Crossing capabilities of the parametric algorithm in Digital Fabrication strategies and capabilities of a standard production system of GLT, authors discuss whether Parametric and Generative Design techniques may enhance Mass-Customization capabilities in the BI, pushing the whole production system towards more efficient processes.

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1. Introduction

According to Italian Institute of Statistics (ISTAT), the Building Industry (BI) is characterized as one of the less efficient industries on the market and the productivity gap with other industries have been growing up [1] in the last decade. This lack of efficiency in BI is mainly due for the following reasons:

- The BI is a highly customized Engineer-to-Order (ETO) industry. This means that every product has to be engineered as soon as an order from a customer is delivered.
- The supply chain system is structured according to a rigid serial workflow that does not always allow to prevent errors among the supply chain itself.
- A front-end strategy supported by a digital information management is missing and errors have to be solved time by time.

One main reason for low-efficient processes in the BI is the high amount of customized work content. Traditionally, projects in the BI are characterized by highly customized products and components. In the case of timber building industries, companies have to realize customized timber houses in shortest time, with lowest costs as possible and with a high

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attention to the individual needs and requirements of the single customer. To improve efficiency of such customized building projects this work shows an approach using Parametric and Generative design techniques. Through the application of the proposed approach and algorithm building companies in the timber sector, should be able to increase industrialization in a typically handcraft sector maintaining and maximizing the grade of customization needed in this special environment.

Mass-Customization as a combination of highly industrialized mass production and customized craft production is the response from the manufacturing industry to the requirements of an increasingly modern and dynamic world. The increasing desire for individuality of people promotes the trend towards Mass-Customization. The producer, which is able to produce a product to low prices and with customer specific characteristics as quickly as possible, has the highest competitive advantage on the market. Simultaneously, new technologies such as advanced web technology, digitalization or additive manufacturing technologies have opened new possibilities for capturing customer requirements and for producing customer-specific products. Mass-Customization is combining the highly controversial objectives of individualization and cost-efficient production and allows maximum flexibility producing products with a reasonable cost structure [2].

2. Theoretical background – state of the art

There are already many studies on Mass-Customization in the literature. In this paragraph authors will first discuss the basic theory of Mass-Customization based on a brief literature review. In the next section the current state of Mass-Customization in traditional manufacturing processes and subsequently in the BI is explained.

2.1. The concept of Mass-Customization

It has been shown by empirical and simulation studies [3, 4] that increased product variety has a significant negative impact on the performance of manufacturing processes. The higher the number of product variants, configurations or overall variety, the more complex difficulties in the production design and operational management of production systems or supply chains are [5]. Mass-Customization has been identified as a competitive advantage strategy by an increasing number of companies [6] to overcome these difficulties. The concept of Mass-Customization was first expounded formally in the book "Future Perfect" by Stanley M. Davis in 1989 [7]. Mass-Customization means manufacturing products, which have been customized for the customer, at production costs similar to those of mass-produced products [8]. Mass-Customization allows customers to select attributes from a set of pre-defined features in order to design their individualized product, by which they can fulfill their specific needs and take pride in having created a unique result [9, 10, 11] Thus, customization integrates customers within the design process [12]. The primary focus of the product designer should be on providing value to the end user. To achieve personalization increasing the value for the end user, different authors suggest a user-centered design approach. [13].

2.2. Mass-Customization Manufacturing

Numerous authors have published articles about Mass-Customization; many of them discussed Mass-Customization from a strategic and economic point of view. Only few works investigate technical aspects of manufacturing and manufacturing systems design of mass customized products [14, 15, 16 and 17]. Mass-Customization Manufacturing (MCM) has been gaining recognition as an industrial revolution in the 21st century. Customers usually can select options from a predetermined list and request them to be assembled [12]. While the manufacturing industry in the past distributed globally standardized products to keep the production cost and complexity low, nowadays a customization of products based on customer specific needs is becoming more and more important [17].

Manufacturing systems in a Mass-Customization environment should be able to produce small quantities in a highly flexible way and to be rapidly reconfigurable [12, 19]. Such a manufacturing system fits the needed requirements for Mass-Customization manufacturing better than a traditional one. The latest trend in Mass-Customization is digitalization in manufacturing, also known under the term "Industry 4.0" or "Cyber-Physical-Systems" (CPS). The large potential of Industry 4.0 will be a key enabler for further developments in Mass-Customization manufacturing [19]. To reach such a next level of changeability it is necessary to equip manufacturing systems with cognitive capabilities in order to take autonomous decisions in even more complex production processes with a high product variety [20].

2.3. Mass-Customization in the Building Industry

Mass-Customization has been used inadvertently in the BI since a long time. But only very little and scattered systematic attempts have been made to apply it within the field [21].

Also in the BI there could be recognized a growing trend in customization and thus in mass customized products or objects. Frutos and Borenstein [22] developed in 2004 a prototype implementation of a web based information system framework for agile interactions between building companies and customers for flat customization for a Brazilian building company.

In the Korean housing market the level of customization for houses has been restricted by economics of scale in the construction processes. Shin et al. [23] described in 2008 their Finishing Information System (FIS) approach based on a case study in a real apartment complex project. FIS is a web-based interactive design program to configure and visualize customized housing solutions and extra options.

According to Bock and Linner [24] customizations' heart in the BI is information and communication technology used for forming continuous IT structures on which those information flows are then created. Customization is deeply based on the evolution and interconnection of all computer based technologies.

According to Jabi´s definition, Parametric Design is "the process 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" [25]. This relationship is expressed through a connection 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. Parametric and Generative Design techniques are more effective in decision-making processes, in case of information and relationships that have to be defined [26]. Nowadays, computers aid the algorithmic thinking, and script programming is the formal expression of design algorithms. Thanks to a uniform and explicit language (scripts), it is possible to manage information among different responsible figures efficiently in the value-chain system.

Parametric and Generative design techniques show a potential tool not only for supporting a quick design of customized products, but also a potential for designing products in a way, that reduces complexity in manufacturing as well as installation on-site. In Parametric and Generative design techniques, properties of objects are defined by parameters and relationships among parameters and thus, they are highly flexible. 3D Building Information Models (BIM) are becoming more and more important for data exchange in the BI [25, 27].

In the following, the authors present an overview of a research activity aiming at testing whether Parametric and Generative Design techniques may enhance Mass-Customization capabilities in the BI.

3. Programming a parametric and generative algorithm for GLT design and engineering

As first step, the research team developed a specific parametric algorithm in order to push a more efficient and a more effective digital information management among design and engineering processes in the production system of GLT. The parametric algorithm pursues two specific design intents:

- reducing the usage of unneeded high-quality raw material;
- improving the overall efficiency of the production system of GLT without any change in the production system itself.

Nowadays, it is possible to fulfill these design intents according to specific approaches suggested by the German standard DIN 1052 and the European standard EN 14080. The algorithm has been programmed in order to enhance the capabilities of these approaches. By this way, the only difference between an ordinary process and the one applying Parametric and Generative Design techniques is the algorithm itself. Thus, authors have been able to measure only impacts produced by the algorithm without pushing any change in an ordinary production system of GLT.

The algorithm requires specific inputs that have to be manually set in order to perform its calculation:

- a free form 3D model of the GLT structural element that has to be manufactured (NURBS solid, NURBS surfaces or poly-surfaces);
- an overall discretization interval (between 10 and 100 mm) for curvature analysis and plotting FEM results;
- loads, supports and their degree of freedom for FEM calculation purposes.

Through specific calculation stages the algorithm defines the key parameters for GLT manufacturing such as:

- position (in a X,Y,Z reference system) and strength class of laminates along the main axes of the element and along the width of the cross section;
- lamination thicknesses along the two main axes parallel to main curvature planes (Y- and Z-axes).

For further details about the parametric algorithm, authors kindly invite readers to refer to previous publications [28].

3.1. Value-Stream Mapping of an ordinary production system of GLT

According to Erlach [29], VSM is an effective modelling strategy to define a factory's value stream in every element (such as production processes, business processes, material flows and information flows). The main goal of VSM is "the efficient mapping and clear description of the currently existing situation in a factory in order to gain a better understanding of the current production process and to pint out potential for improvements" [29]. The analysis is performed through a snap-mapping method to define typical factory conditions. In two consecutive runs, starting from the customer end, first the production flow and then the order flow are mapped by way of interviews, measuring and counting.

Authors identified every element of the production and the order flow of an ordinary production system of GLT performing specific surveys at a cooperation company, which is the biggest manufacturer of GLT in the Italian market. The VSM has been visualized according to the symbols tool box defined by Fraunhofer IAO research institute [30]. After identifying the Customer Takt Time (TT) on the basis of the annual production-rate or the objective production-rate (indexed by m^3 of product, by orders and by GLT elements per order), authors identified the Operation Time (OT), the Changeover Time (CO), the Coverage index, the UP Time (UP), the process-related Working Time per day (WT_p) and they calculated the EPEI factor for each stage of the production flow. The EPEI (Every Part – Every Interval) is the time required by the entire changeover cycle for all variants. In case of ETO industries, such as the GLT one, the EPEI value can be referred to the entire changeover time per order, considering that the production flow restarts as soon as a new order is delivered. Thus, the EPEI can be calculated as follow:

$$EPEI = \frac{\frac{1}{\uparrow} \cdot \sum OT + \frac{1}{Cov} \cdot \sum CO}{RES \cdot UP} \left[\frac{\text{h}}{\text{order}} \right] \quad (1)$$

where ↑ is the first pass yield [%], *OT* the Operation Time per element type, *Cov* the Coverage index [%], *CO* the Changeover Time, *RES* the number of Resources available [pcs.] (such as machinery or workers) and *UP* the Uptime [%].

EPEI may be compared with the process-related Takt Time (TTp) in order to identify possible bottle-necks along the production flow. The process-related Takt Time (TTp) can be calculated as follow (indexed by m^3 of product, by orders or by GLT elements per order):

$$TTp = \frac{FD \cdot WT_p}{Pcs}\left[\frac{\text{sec}}{\text{m}^3} \text{ or } \frac{\text{h}}{\text{order}} \text{ or } \frac{\text{min}}{\text{elem}}\right] \quad (2)$$

where *FD* are working days per year [days], WT_p the process-related Working Time per day [time unit] and *Pcs* the annual amount of product [m^3, orders or structural elements].

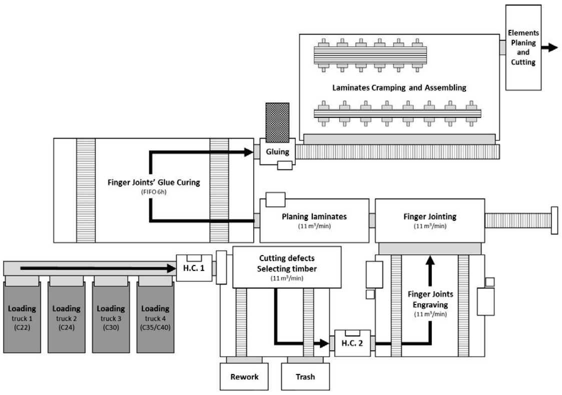

Fig.1. Draft layout of production flow stages.

Once all stages of the production flow have been defined, authors identified the Operation Time (OT), the Process Time (PT), the Coverage Rate and the process-related Working Time per day (WT_P) for each stage of the order flow. Finally, material flows, storages and information flows have been identified, represented and properly connected in the value-stream map.

After completing the modelling of the ordinary production system of GLT, authors identified specific stages along the production and the order flows that may be influenced by parametric algorithm's application. On these stages, specific simulations have been performed in order to identify potentials and criticisms of applying Parametric and Generative Design techniques to an ordinary production system of GLT. Simulations highlighted capabilities of the ordinary production system handling high-customizable contents in terms of EPEI factor and total Lead Time.

4. Application of Parametric and Generative Design in an industrial case study and results

The cooperation company performs all ordinary stages of the GLT manufacturing on-site, except for the strength grading of sawn timber, which has to be performed by the sawmill providing the raw material. Thus, the production flow of the cooperation company includes the following stages: Fig. 1 shows a draft layout of these stages along the production flow.

After a first humidity check of the sawn timber, defects near to the finger-jointing edges are cut out, if needed. On a second stage, an automatic milling machine drills finger-joints and glues the sawn timber in order to obtain laminates of the desired length. Laminates are planed and stored for 6 hours waiting for glue curing. On a third stage, glue is applied on the main surface of laminates and they are manually laid-up into jigs for cramping of final GLT elements and waiting for glue curing. Finally, GLT elements are moved for final planning and finishing. Finishing may include painting, installation of steel connections, packaging and labelling; these final steps may change order by order, according to specific customer requests. In case of doubled curved elements, craping stage has to be performed twice: the element is cramped according to the first curvature along the main plane; once the element is ready for finishing, it is cut and cramped once again according to the curvature along the plane perpendicular to the main one.

The order flow includes several stages: the cooperation company performs not only stages for leading the manufacturing process and managing orders and sales, but also some optional stages, which may be requested as an additional service by customers (such as structural engineering). Thus, the cooperation company can handle two types of order: provisions of GLT elements according to individual customers' specifications or complete structural services from designing of an entire GLT structure. As average indication, the cooperation company declared that simple provisions of GLT are the 50% of the yearly total amount.

Considering an average annual production rate of 25.000 m^3 of GLT delivered throughout 200 orders of 50 structural elements each, the overall value chain system of the cooperation company can be summarized as in the value-stream model shown in Fig.2.

Referring to EPEI factors and process-related Takt-Time values, the cooperation company does not present any lack of efficiency along the production-system until variants per each order are limited to 3 element types (Coverage index of 33%). As element type, authors identified the final strength class of a GLT element according to EN 1194 Thus, the cooperation company arranges orders and the production flow in order to manufacture maximum 3 different strength classes per order.

Introducing the programmed parametric algorithm as digital tool for GLT engineering, authors identified specific stages that are influenced by parametric algorithm's application. These stages are highlighted in Fig.2.

Along the order flow, any change cannot be measured. Structural engineering stage may save until 30% of Operation Time, but this time has to be spent for preparing inputs for the parametric algorithm which will be used in product engineering and production plan stages. During these stages, data for the machinery leading finger jointing, planning and cutting have to be set and loaded to the machinery itself. This operation determines the Changeover Time in the early first stages of the production flow. As shown in Fig. 3, the algorithm allows to increase the number of variants from 3 to 50 without overcome the process-related Takt-Time, considering 80 seconds as Changeover Time.

The programmed algorithm takes 8 seconds to perform the entire calculation on a personal computer with a CPU-singlethreaded score of 1486 (according to PassMark® test). Any increasing of calculation time has been measured against increased complexity of input data (GLT element to be manufactured): the algorithm perform just a calculation per single element, increasing complexity in the overall structure does not afflict the algorithm itself.

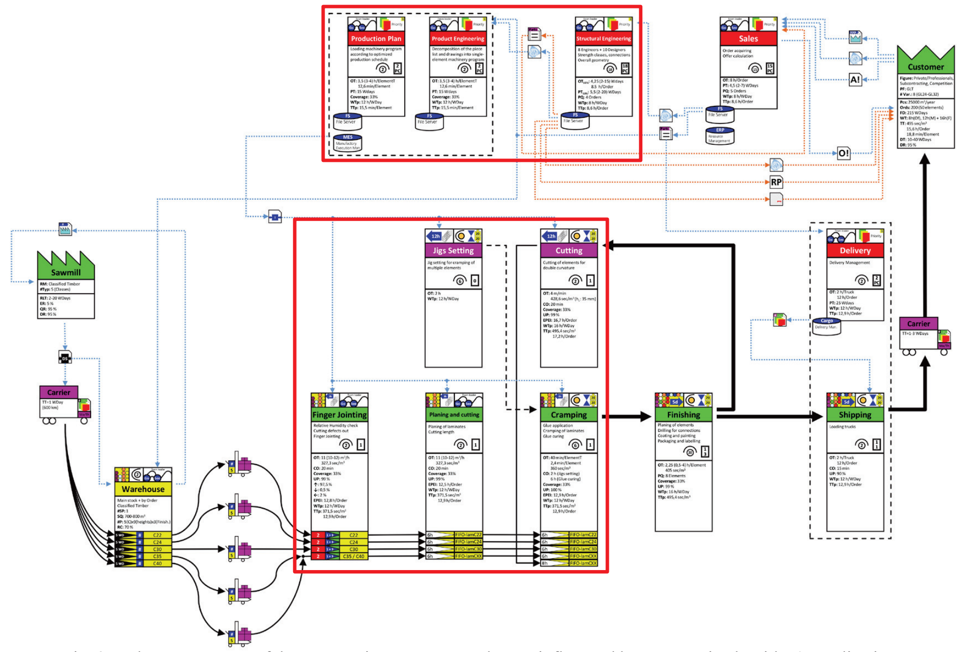

Fig. 2. Value-stream map of the cooperation company and areas influenced by parametric algorithm's application.

Recording that a worker may take up to 30 seconds to load data into the algorithm, the definition of input data for machinery (so-called Digital Fabrication) has not to take longer than 42 seconds. This limit can be respected only through a digital-data transfer between the algorithm and the manufacturing machinery along the production system. Unfortunately, the manufacturing machinery's software is property of the machinery's manufacturer and the cooperation company could not provide any detail about input requirements (nowadays data are set manually). For this reason the Digital Fabbrication step has not been implemented yet in the programmed algorithm. Furthermore, it has to be considered that this step has to be programmed case by case, according to different machineries adopted. At this stage of the research, it is not possible to estimate clearly the effort for the Digital Fabbrication step implementation. The algorithm has been programmed in order to output just drawings and part lists, which are the ordinary format for information flows at the cooperation company. The effort for the implementation of this final step depends from the input format that the manufacturing machinery's software can handle. Further investigations have to be performed involving machinery's manufacturer also.

Finally, any reduction of the total Lead Time cannot be measured. This implies that the cooperation company can increase the number of variants from 3 to 50 (which means every single GLT element different from other ones) without any lack of efficiency along the production system or any delay in deliveries, but any improvement in delivery time cannot be introduced until some stages along the production system are leaded in an ordinary way such as manual laying-up and cramping of GLT elements.

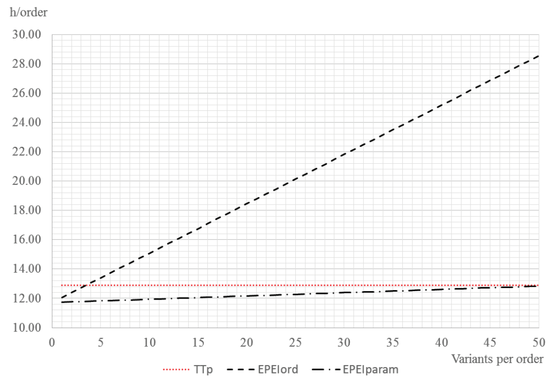

Fig. 3 Comparison between EPEIs for ordinary production system of GLT and the one applying Parametric and Generative Design Tecniques (considering 80 sec. as Changeover Time)

5. Conclusions and outlook

Referring to the industrial case study presented, Parametric and Generative Design techniques are effective tools for pushing Mass-Customization in BI reducing or eliminating any lack of efficiency along an ordinary production system. Anyway, in order to produce improvements in terms of total Lead Time, changes in specific stages of the production system have to be introduced and to be further studied.

Authors remark that the programmed algorithm needs several improvements before trying to adopt it in daily manufacturing activities of the cooperation company, in details:

- The curvature analysis has to be fully implemented with Digital Fabrication steps that has to be programmed case by case.
- The output management through Digital Fabrication strategy has to be validated case by case according to production flow stages in order to provide effective outputs.
- The FEM simulation step has to be fully validated.
- The algorithm has to be stress-tested by designing and engineering some prototypes, which have to satisfy different customer's needs randomly generated. Prototypes has to be mechanically tested in order to state the reliability of the algorithm.

Furthermore, referring to the case study discussed in this paper, the following activities have to be accomplished in order to increase the reliability of the discussed results, which have to be considered just a promising starting point.

- Future research activities aiming at implementing a parametric and/or generative algorithm in ordinary production system of GLT have to involve machines' manufacturers also in order to introduce automations in information management platforms.
- In order to enhance impacts of Parametric and Generative Design techniques on ordinary production system of GLT, changes in information management platforms, in production system layouts or in machinery setup have to be introduced. For this reason, investment plans and payback evaluations have to carried out before implementing Parametric and Generative Design techniques on ordinary production system of GLT.

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