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CARES research: product and process digitalization for design and manufacturing of prefabricated cardboard panels

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Abstract. Building prefabrication is facing the challenge to reduce the life-cycle impact of construction, enhance material circularity, and increase the quality of building products and processes. The paper presents the first phase of the research CARES - CARdboard RElocatable School developed with the Italian brand Archicart by Area S.r.l with the aim to prototype a temporary school unit. The work presented is focused on the industrialization of a prefabricated building technology based on the use of cardboard panels (PACOTEC™ Stre-Wall panels). Cardboard is a circular and environmentally sustainable material but currently the design and manufacturing process lacks digital integration, resulting in poor quality control, limited adaptability, and lack of material optimization. To address sustainability goals, the work implemented a “file-to-factory” approach to redesign the design-manufacturing process of prefabricated cardboard panels, integrating industry 4.0 paradigms in manufacturing (automation, high-precision manufacturing) and the use of BIM tools for design to achieve better product-process quality and predictability. The redesigned workflow allows achieving sustainability goals, such as reduction of errors, reduction of material wastes, cost and time predictability, product customization, and adaptability. The workflow will be verified and tested in the design and manufacturing of prefabricated cardboard panels to build a temporary school unit.

1. Introduction

Nowadays, building prefabrication is going through major changes in its practice. Firstly, there is an increasing concern about the environmental, economic, and social sustainability of the Architecture, Engineering, and Construction (AEC) sector [1,2]; indeed, international policies aim to reduce the life-cycle impact of construction, to enhance resource circularity, and to increase the quality of building products and processes [3,4]. Secondly, the market needs to meet a new demand for product customization, shifting from standardization to mass customization (i.e. creating bespoke solutions with the same cost as mass-produced ones) [5]. In the last years, prefabrication adopted new approaches to deal with the greater complexity of design and manufacturing of building components, and achieve sustainability goals, such as resource optimization, improved quality, and flexibility for customization. Within the design, “file-to-factory” strategies streamline the transfer of building specification to manufacturing, enabled by the digitalization of prefabricated building components with Building Information Modelling (BIM) tools that facilitate the integration of information, design tools and manufacturing equipment [6]. Moreover, manufacturing shifts towards industrialized production, integrating industry 4.0 paradigms as automation and use of high-precision machines (Computerized Numerical Control CNC, laser cutting, 3D printing) to achieve tighter control over final products, and easy reconfiguration of the process for mass-customized design specifications [7].



At the same time, circular economy principles drive scientific and industrial research towards the use of innovative materials, with high performances and reduced life-cycle impact [8]. Among these, recent case studies proved that cardboard can be effectively used to prefabricate building components [9,10]. However, examples are still experimental and there is not a stable market offer of cardboard components for buildings. In Italy, the company Archicart¹ developed the use of prefabricated cardboard panels (PACOTETM Stre-Wall) for building construction. Based on preliminary investigation, the technology shows high circularity, since cardboard comes from recycled sources and can be recycled at the end of the use; moreover, prefabricated panels can be disassembled and relocated, extending the life-cycle of the building [11].

However, the current design and manufacturing sequences are craftsmanship-based and there is a lack of integration of IT technologies within the process; this results in limited quality control over the final product and process (time, costs) and a higher risk of errors, as well as limited flexibility for panels' customization.

In this scenario, the paper presents the first results obtained within the research CARES - CARdboard RElocatable School unit, developed in collaboration with the company Archicart to initiate an industrialization process of prefabricated cardboard panels for temporary school buildings. According to existing work analyzed, digitalization and automation are assumed as strategies to enhance technology sustainability in terms of product and process quality, resource optimization, and prefabricated building adaptability. The research methodology consists in the analysis and re-designing of cardboard prefabricated panels' design and manufacturing workflow through product-process digitalization and manufacturing automation according to a "file-to-factory" approach, enabled by the use of BIM tools. The redesigned workflow allows addressing sustainability goals, such as reduction of errors, reduction of material wastes, cost and time predictability, product customization, and adaptability.

2. Design and manufacturing process of prefabricated cardboard panels: workflow analysis and research objectives

In the first phase of the research we have analyzed Archicart's workflow of panel design and manufacturing (Figure 1). The aim was to describe sequences, methodologies, and tools adopted within different phases, as well as to highlight issues connected with the current management structure. The building technology uses prefabricated cardboard panels to form continuous load-bearing vertical and horizontal envelope systems [11].

Currently, the design phase (Phase 1, Figure 1) process is based on the use of Computer-Aided-Design (CAD) software for concept and executive design, while cost evaluation and material orders are managed with spreadsheet templates. In the second phase (Phase 2, Figure 1) the Italian company transforms the cardboard sheets into tubules, by a workforce-based process of cutting, folding, and gluing according to executive design specifications. Later on, panels are integrated with natural fiber insulation, wooden boards, and posts and then transported to the installation site (Phase 3, Figure 1).

The analysis led to the detection of the following weaknesses in the process:

- Lack of flexibility in product customization due to Computer-Aided-Design (CAD)-based design approach; indeed, for each project, personalization requires manual reconfiguration of executive specification, verifications, and updating drawings.
- Absence of vertical organization of the process (i.e. lack of connection between information throughout phases) with the consequence of time and cost increase.
- Higher risk of errors and discrepancy between design specification and final product, because of workforce-based manufacturing.

¹ Archicart is a mark of the Italian innovative SME Area srl based in Catania (Italy) specialized in design and manufacturing prefabricated cardboard panels based on the patented technology PACOTE[®].

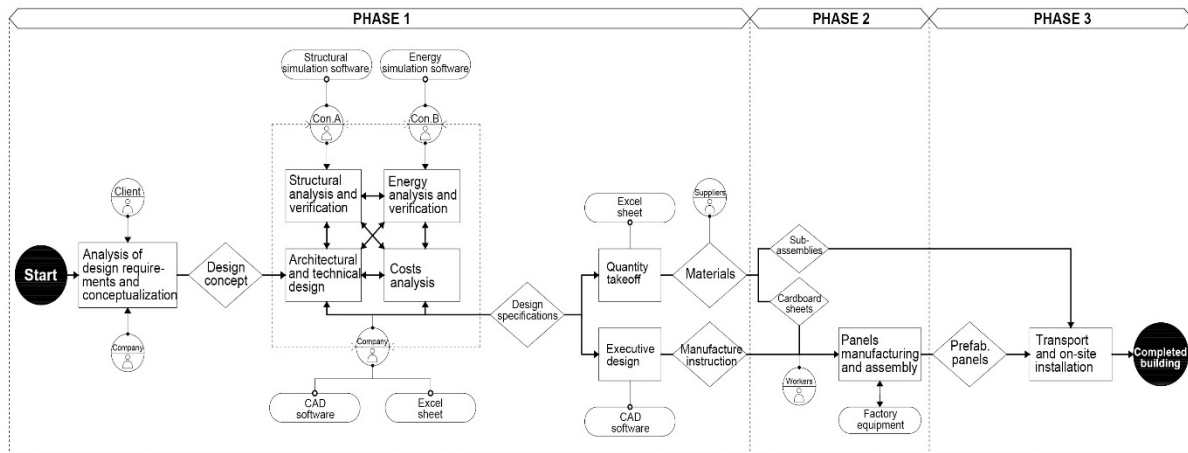


Figure 1. The flowchart represents the current sequences for design and manufacture prefabricated cardboard panels

In the second phase of the research CARES (developed in collaboration with the company Archicart) we have defined the following operative objectives, in order to redesign the company’s product-process workflow (through BIM software), and to promote flexibility, customization, and life-cycle analysis by digitalization and automation:

- OB.1) Adaptability: flexibility in customization of prefabricated cardboard panels.
- OB.2) Predictability and verification: real-time checking and material/costs computing for different design options.
- OB.3) Resource optimization throughout the process (materials, costs, time)
- OB.4) Product quality control: direct implementation and transfer of executive panel specification from design software to manufacturing equipment.

3. Workflow redesign for design and manufacturing prefabricated cardboard panels

To address the research objectives, the research work re-designed the company’s process based on the concepts of product digitalization and manufacturing automation according to industry 4.0 paradigms identified by previous research of the authors [13] (Figure 2):

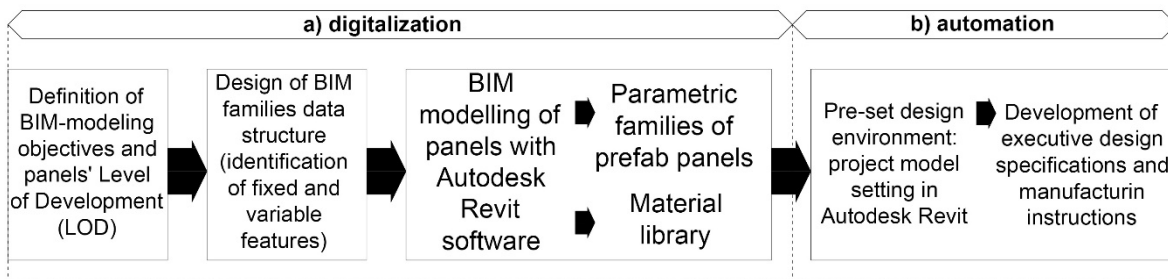


Figure 2. Proposed methodology and approaches for redesign the workflow of design and manufacturing prefabricated cardboard panels

a. Digitalization of prefabricated cardboard panels i.e. developing BIM models according to the following and subsequent phases of implementation (Figure 2): 1) definition of the Level of Development (LOD, UNI 11377-4: 2017) according to operative objectives; panels are modelled as Detailed object - LOD D; 2) design of BIM parametric model data structure, discretizing the panel features in fixed and variable to balance modification options with model complexity; 3) developing parametric digital models of three basic types of prefabricated cardboard panels with Autodesk Revit® software to be integrated in the design of CARES school unit (vertical, shaped, and horizontal panel) and that can be customized to obtain different panel typologies, i.e. implementation of external families (.rfa file extension) that can be exchanged and uploaded in BIM software, and integrated with other standard components;; 4) creation of a material library to collect thermo-hygrometric (thermal conductivity, specific heat capacity) and economic (€/smq) features to implement the BIM families; 5) creation of a pre-set design environment (i.e. a project model developed with Autodesk Revit®) to upload the panel families, visualize the 3D model of the school unit and, at the same time, schedule templates with total amount of material and costs, enabling real-time design checking.

b. Manufacturing automation to transfer design specification from BIM model to manufacturing equipment (Figure 2), i.e. creating a dedicated working space inside the Autodesk Revit® project model of the CARES school unit to associate panels' customized specification to cardboard sheet dimensions and cutting/folding lines positioning, to calculate the maximum dimension of the cardboard sheet purchased them from suppliers according to design needs, optimizing material resources and limiting wastes. Moreover, the distance between cardboard sheet and cutting-folding tools can be reported as parameters list in a specific schedule and exported as a data file; in this way, information can be transferred to the cutting and folding machine as processing input. This is possible thanks to the use of new manufacturing equipment that has been specifically designed by the company to enable digital management of manufacturing.

4. Results and discussion

The redesign of the product-process workflow of prefabricated cardboard panels (PACOTEC™ Stre-Wall) for the CARES temporary school unit achieves the following research objectives:

- Production of prefabricated panels that can be easily adapted to different design requirements according to mass-customization principles: in fact, changes in panel parameters during design do not require variation in the following sequences (OB.1);
- Design of new envelope technological solutions that can be simultaneously verified according to the building program in order to analyze their energy, environmental and economic performances (OB.2);
- Optimization of the materials according to panel specifications, limiting waste and excessive costs (OB.3);
- Performing tighter controls over prefabricated panels, since direct communication between BIM parametric design and manufacture equipment reduces the possibility of errors and, together with the use of high-precision manufacturing, ensures consistency between design specification and the final product (OB.4).

In this perspective, the research CARES demonstrates that integration of industry 4.0 paradigms and IT technologies in building design and manufacturing management strengthens the environmental, economic, and social sustainability of Archicart's prefabricated cardboard panel technology. The result led to the description of a new flowchart that summarized the new design and manufacturing sequences based on IT tools (Figure 3). The redesigned workflow, which has a vertical structure (i.e. the processes are automatized thanks to the use of pre-implemented digital models), summarizes sequences, methodology, tools, and output for each phase.

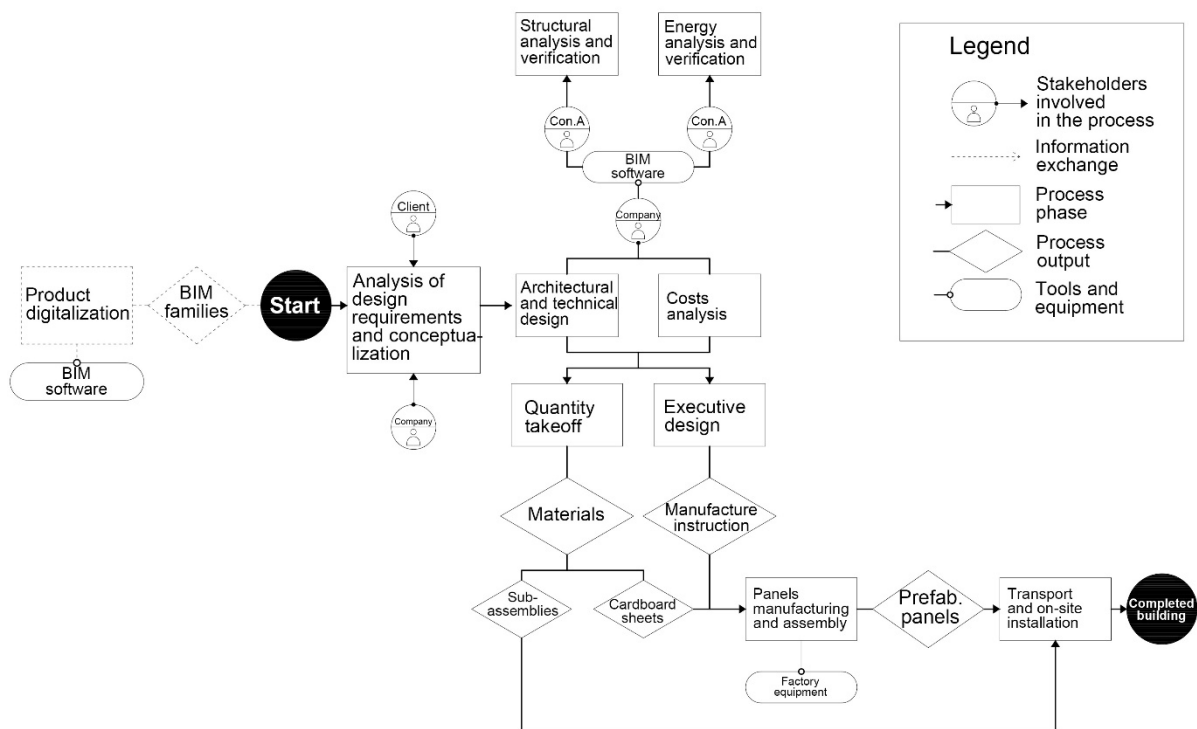


Figure 3. Redesigned workflow based on product and process digitalization and automation

The integration of IT technologies in the design and manufacturing of prefabricated cardboard panels allows optimizing the horizontal and workforce-based process that limit panels' adaptability, quality control, and predictability. In this perspective, the work applies digitalization and automation as the main strategies to redesign the panels' design and manufacturing process and achieve enhanced product-process performances. The work establishes a reference case for sustainable industrialization of environmentally-friendly building technology, based on recycled and recyclable material that has low environmental impact. The outcome is a BIM-based workflow that allows streamlining design sequences, verify costs and performances, optimize material resources (number and dimension of cardboard sheet) and operate tighter controls over the product and process. The workflow will be verified in the next phase of the research CARES – CARdboard RElocatable School unit, i.e. it will be tested for the design and manufacturing of a temporary school unit using prefabricated cardboard panels. The proposed workflow will be evaluated according to quantitative parameters as percentage of time and cost reduction compared to the current organization, reduction of emissions, and decrease of energy usage within the process.

Further implementation of the work concerns the integration of BIM-based families with simulation tools for structural and energy-performances evaluation, particularly their integration with structural and Building Energy Modelling software [12].

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