Improving Construction Efficiency with Digital Fabrication.
An Environmental Insight

Kuzmenko K1,2, Féraille A1, Baverel O1
1Laboratoire Navier, UMR 8205. Ecole des Ponts ParisTech, IFSTTAR, CNRS, 6-8 Av. B. Pascal, 77455 MLV Cedex 2
2Kardham C&H Architecture, 10 rue du Débarcadère 75017 Paris
kateryna.kuzmenko@enpc.fr

Abstract. This paper presents a case study of environmental evaluation of innovative shell-
nexorade hybrid timber construction system designed within fabrication-aware technic and
fabricated using robotic construction technology. The life cycle assessment of construction phase
of the system has been performed; a sensitivity study of the robotic system’s outlay has been
effectuated. The results show that the contribution of robotic construction system to the overall
result is fairly significant and, in some figures, can even exceed the material’s one.

1. Introduction
The ongoing development of digital design and fabrication techniques has explicitly changed the way
architecture is thought, designed and produced. The emergence of the non-standard movement in the
early 2000 was explicitly arguing for the beginning of the new era based of mass-customization
paradigm, that was supposed to bring some spectacular changes to construction industry by releasing its
production from the curse of standardization [1],[2].

Therefore, empowered by computation, a whole generation of highly optimized forms appeared,
spreading a belief into the sustainable character of those as well as the potential of digital technologies
in the field of environmental performance of the sector.

Nevertheless, most of optimization and rationalization technics are principally focused on a single
phase of life cycle of a product or a single impact indicator. Today’s most of energy-efficiency policies
are focused on the operational phase of a building, e.g. heating, cooling, etc [3]. And a recent slight
progression towards life cycle performance generated a hot discussion amongst practitioners on
ecological character of different construction materials, with a succeeding popularity of timber high-rise
buildings.

Regarding the academic trends, multiple lightweight construction systems were developed within
digital design-to-production workflow [4], [5]. A significant reduction of construction materials in
various building elements was achieved, strengthening the credence into the sustainable potential of
digital fabrication.

In this paper we question the environmental performance of morphologically optimized and numerically
produced construction system. The use of life-cycle assessment method is proposed to evaluate the
question. An innovative timber construction system - shell-nexorade hybrid is taken as a case-study.

The purpose of the study is twofold: in the first place, the environmental impact of the construction
system is assessed, secondly the impact transfer of the system is investigated. In other terms, the
fundamental question of this work is the possible trade-off between efficiency of the structure and environmental load of robotic construction system.

2. Description of the structure

2.1. Design

The structure was built for the occasion of 20 years of the new site of Ecole des Ponts ParisTech, by the team of Navier Laboratory. Also known as R2 pavilion, the structure incorporates manifold researches on structural morphology and architectural geometry conducted in laboratory.

![Figure 1. R2 Pavilion built with shell-nexorade hybrid structural system](image)

The structural type of the pavilion was baptized as shell-nexorade hybrid, due to the elegant blend of both principles. Nexorades, are largely known as reciprocal frames. They are constituted of load bearing members which support each other in a cyclic manner along their sides [6]. This specific arrangement of members makes them connect by pairs, creating a significant simplification of assembly, which is a general problem of classical space structures and gridshells. However, the simplification of assembly technics comes along with an increase of geometrical complexity, which is usually solved by a form-finding method as far as design part is concerned [7].

The membrane behaviour was achieved by introducing the flat panels that act like bracing elements and transform the grid of beams into the shell structure. Therefore, with an additional 30% of material mass the structural stiffness was multiplied by 10.

The planarity of the bracing quad panels was held within marionette method [8] in order to ensure their fabrication flair as well as to avoid the coupling between bending and axial forces. Therefore, the initial surface was meshed with planar quads, then using translation method [9] the T-joints were generated, preserving the planarity of the quads.
2.2. Fabrication

Most of design choices of the project were made within the fabrication-aware strategy [11], which could be briefly described as the geometry rationalization principle focused on manufacture constraints. Thus, the final structure is composed of 102 straight glulam beams and 48 flat plywood panels, each of which is non-standard. The totality of formal and manufacturing complexity was brought into beam’s geometry (Figure 3), to be held with 6 axes robotic milling. As follows, the panel fabrication was abridged to a mere CNC cut.

The layout scheme of the robotic platform of Ecole des Ponts ParisTech is shown in Figure 4. It is composed of two collaborating 6 axes robotic arms (1): one is mounted on a 9 m track (2) and referred as gripper robot (1a), the other is fixed and referred as fixed robot (1b). The milling head (3) is mounted on fixed robot and the pneumatic gripper (4) is fixed on gripper robot. Next, eight independent operations were effectuated with stationary fixed tools dispatched around the track (cf.[12]).
2.3. Assembly
The assembly technic of the structure represents the most low-tech part of the construction process. It basically demands some drilling skills and some specific crews, that can be set against the wood fibres [13] (Figure 5).

![Figure 5. Scheme of T-connections assembly of Beams [12]](image)

All the construction elements of a structure were prefabricated off-site and assembled in-situ, which demands an approximately zero tolerances of fabrication and assembly processes. The assembly sequence starts from the construction of a hexapod from the central node and then progresses to the boards. Geometric control of connections was ensured through the tenon/mortise system milled on the beam’s extremities (Figure 3) and the adjustment of the bracing panels (cut with a tolerance of 2 mm on each side). Authors claim that the assemblage part can be handled by 2 persons [12], back in time though the human resources needed to figure one were 6 PhD students, 2 Academic Researchers and 1 Professor.

3. Methodology
In order to evaluate the environmental character of the structure, the Life Cycle Analysis method is used [14], [15].

A few academic works have already explored a similar problem. Agusti-Huan et al. have effectuated a foremost work in the field, comparing digitally fabricated elements with ones fabricated conventionally [16], [17], concluding that digital fabrication processes do not really count in total results, comparing to the potential in terms of material reduction they bring. The system boundaries of the analysis were cradle-to-gate, without consideration of end of life phase.

Krieg et al. have also performed an LCA study of an innovative timber structure [18]. The constructive system was compared with its alternatives, differentiating materials and fabrication technics. The stiffness of the structure was referred as functional unit and only the GWP indicator was considered. The results show that even if the embodied carbon of materials is still more important than the one of robotic construction system, the second does contribute to global result. It seems that only energy consumption of the robot was taken into account.

In present case study we focus on the methodology for taking into account robotic construction system. Therefore, a detailed life cycle model of robotic fabrication system was assembled, taking into account the maintenance and the replacement of components during service period that was set for 12 years. Then, a sensitivity study of the outlay of the construction system to the referenced process was effectuated, ranging a working period of machines within three scenarios (Table 1) in order to investigate the difference it will bring to global result. The outlay calculation follows the expression below:

\[
\text{Working Period of Machine} \quad \text{Lifespan of Machine} \quad 100\%
\]

The first one considers uniquely the fabrication time which is around 20 minutes by beam and one hour for panels. The second one reflects an idealistic scenario of the entire production process: one week
by machine, which still is greatly optimistic for the research project. The third scenario accounts an actual duration of parametrisation and set up period needed at the time: two months for robotic cell and two weeks for CNC cell. It is important to note that the energy consumption remains the same in all three scenarios.

| Table 1. Three scenarios of machines’ outlay |
|--------------------------------------------|
|                                           |
| **Robotic Cell’s Outlay**                  |
| 1st Scenario                              |
| 37.62 H / 105120 H = 0.04%                 |
| 2nd Scenario                              |
| 120 H / 105120 H = 0.1%                    |
| 3rd Scenario                              |
| 1440 H / 105120 H = 1.4%                   |
| **CNC Cell’s Outlay**                      |
| 1st Scenario                              |
| 1 H / 175200 H = 0.0006%                   |
| 2nd Scenario                              |
| 120 H / 175200 H = 0.07%                   |
| 3rd Scenario                              |
| 576 H / 175200 H = 0.3%                    |

In order to have comparable results regarding other construction technics, the cradle-to-gate stages were set as system boundaries (A1-A3 cf. EN 15804). Recipe Midpoint (H) method of impact calculation was chose, following to the ILCD Handbook recommendations [19]. The EcoInvent 3.2 cut-off database was used for inventory within OpenLCA software. Finally, the life cycle model of the system is depicted in Figure 6.

4. Results and Discussion
The environmental impact of the shell-nexorade hybrid construction system is presented on the Figures 7 and 8. The variation in results is related to different outlay calculation of robotic and CNC cells to the process of reference. In other terms different working time of machines were considered in order to investigate the sensitivity of the parameter.

The present study illustrates that digital fabrication processes contribute significantly to the overall environmental impact of the system, which means that optimisation design strategies based on robotics technology for the production part should take into account the environmental load of the last.
The same hypothesis needs to be verified for the structure of larger scale containing more elements. Considering the important amount of time needed for the parametrization of production sequence versus the rapid execution, the environmental load of digital fabrication may be insignificant for larger production series. Finally, the present results need to be compared with an alternative construction system fabricated without robotic technology, in order to have the complete vision.

Figure 7. Environmental Impact of Shell-Nexorade Hybrid _ 1st Scenario (above), 2nd Scenario (below)
5. Conclusion

This LCA study of innovative timber construction system designed within the fabrication-aware strategy and produced using digital fabrication technics demonstrates the occurring of an important impact transfer in the life cycle of the system caused by robotic fabrication technology. The sensitivity analysis of the outlay of machine’s working time has confirmed the significance of this parameter in the overall result. Consequently, depending on the accountment method the contribution of digital fabrication system can be almost as important as the one of the materials, which answers the fundamental question of this work on the possible compromise between those two.

In closing, automation in construction is today’s one of the most major research topic in building sector. In early 2000, numerical controlled machines were theorised as the solution for the differentiated mass production, in middle 2010, robotics begun to be seen as the solution to the environmental problem of the sector. Yet, for multiple reasons of legal and technological inertia of the industry, the mass-customisation is barely ready to advent, and the environmental performance of automation remains to be developed within the appropriated theoretical agenda.

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