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Impact of Robotic Circular Wood Processing: lessons from the "One Plank" Challenge – using the AUAS Circular Wood KPI Framework

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Abstract: Wood is an increasingly demanded renewable resource and an important raw material for construction and materials. Demands are rising, with a growing attention for re-use and upcycling, opening up opportunities for new business models, empowered by the use of digital design and technologies. A KPI framework was developed to evaluate the environmental, social, and economic aspects of using recycled wood in robotic manufacturing. This paper explores the use of this framework, focusing on a case study: the "One Plank" Challenge. The study reveals that environmental gains from using waste wood are comparable to production burdens, with significant variation depending on wood type. Production time, encompassing both human and robotic aspects, significantly impacts cost-effectiveness. The findings underscore the importance of considering lifecycle impacts in promoting sustainable robotic manufacturing practices.

Introduction

Wood is a valuable and sustainable material within the circular and biobased economy, because it can store CO_2 if grown and harvested correctly (Szulecka, 2019). Consequently, construction, interior architect-ture and product design are re-discovering timber wood as a sustainable material, creating increasingly higher demands. In a high-growth scenario, total European wood demands are expected to increase with more than 50% in 2030, compared to the 2000-2012 average (Jonsson et al., 2018).

Yet, 25% of the wood used turns into waste after its first lifecycle (van Bruggen & van der Zwaag, 2017), and mostly ends up in landfills or co-firing plants, and to smaller extent is downcycled into chips for particle or fibre board (Besserer et al., 2021). To retain value and enable material and cost savings, cascading and repurposing waste and residual wood are important circular business model strategies (Lüdeke‐Freund et al., 2019). In fact, waste wood is increasingly being harvested for re-use during building renovations or demolitions, at waste collection sites or at wood-related industries (that have left-over pieces from production).

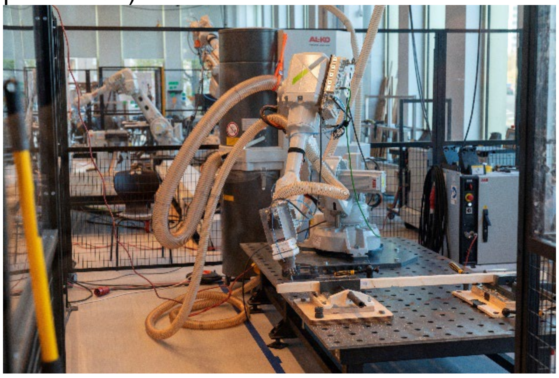

Figure 1. Robotic production with wood at the DPRG Robot Lab

An important strategy to create value from waste and residual wood is the use of digital design and robotic production technologies (Figure 1), as these are especially suited for generating innovative concepts and appli-cations from an uneven wood waste stream (such as left-overs wood from wood manufacturers) which involve a broad variety of pieces with different size, wood type and finishing (Malé-Alemany et al., 2022). Digital design and robotic production can thus support new business models for furniture, interior and building sectors, including direct end-user involvement in design and manufacturing. However, to encourage practitioners to successfully develop circular business models around applications made with waste and residual wood, insight is required on the impact that such applications can make, not only related to environmental (or sustainability) aspects, but also in terms of business and society.

Many tools exist to evaluate the impact of circular applications, on specific aspects like life-cycle analysis (J. Vogtländer, 2014) or material flow analysis (Brunner & Rechberger, 2016). Yet, these tools are not specifically focussed on circular wood use, and the approach used in many of these tools is often too time-consuming (and expensive) to use in practice, thus a more practical tool is needed for business and designers. With the aim to combine existing tools, making them accessible and adding specific wood indicators, the Digital Production Research Group (DGPR) of the Amsterdam University of Applied Sciences (AUAS) composed one integral framework which enables circular wood businesses to select the most appropriate applications and business models for their portfolio. The developed framework (Schoen et al., 2023) intends to support designers to make choices that consider impact not only related to environmental (or sustainability) aspects, but also in terms of business and society.

This paper presents the integral framework ("KPI-framework"), applies it to a concrete research case and briefly addresses specific points for further development.

Research approach

A Key Performance Indicator, or KPI, is a measurable value (which can be both quantitatively and qualitatively measured) that demonstrates how effectively a business, product, employee etc., is achieving their (key) objectives. To assess the impact of a specific application from waste wood, an integral KPI-framework was developed as part of the 'Circular Wood for the Neighbourhood' project (CW4N), coordinated by DPRG. The framework can be used as a tool for the evaluation and comparison of specific applications from waste wood.

The current KPI-framework is a set of nine indicators (see Table 1), derived from a longlist of twenty in total, which can be used to analyse the impact of a circular application made of waste wood using advanced production robotic production systems. In the framework, a specific application (e.g. a stool digitally produced from residual wood) can be benchmarked with a reference application (e.g. a comparable, standard IKEA stool).

Material	
Reused material	% of the product that consists of locally harvested wood
	% of material that is wasted during production process
Circularity potential	% of components which can easily be reused at the end of function
Environmental	
Avoided impacts	Avoided embedded impact from avoided virgin materials
Created impacts	Emissions during production of product
Socio-cultural	
Job creation	(local) Jobs created (high and low educated)
Economic	
Avoided costs	Avoided costs of virgin material use
Created costs	Production costs
	Costs for maintenance and operation or the product

Table 1. Overview of the nine indicators in the KPI-Framework

To calculate the indicators, validated models, databases and calculation methods are used, where available. The actual calculation is performed in an excel model, built and designed with a dashboard to visually summarize the scores. In the next sections, the nine indicators are briefly described, applied to upcycling of waste or left-over wood.

KPI 1.1 Reused material percentage - The percentage of the object (measured in weight) that consists of directly reused materials (mostly wood) in their harvested form. This excludes recycled content in new materials (e.g. new particle board, which can be composed of up to 70% of recycled feedstock).

KPI 1.2 Waste percentage - Calculated as the percentage of material that is lost during production (measured in weight), mostly caused by milling the reused wood.

KPI 2.1 Circularity potential - The percentage of the application that can be easily re-used at the end of its current life cycle. To calculate this, the releasability index method ("losmaakbaarheidsscore”) is used (van Vliet et al., 2021) which focuses on how easily the individual parts of the application can be taken apart again at the end of its lifetime.

KPI 3.1 Avoided impacts - This indicator analyses the avoided environmental impact of using circular materials (predominantly wood), instead of using virgin materials. To calculate this indicator, data from the ecoinvent database is used (Wernet et al., 2016). This database contains embedded CO_2 equivalents (Gohar & Shine, 2007) and eco-costs (J. G. Vogtländer et al., 2002) associated with the specific type of material. This indicator looks only on the material level. It does not consider the environmental impacts related to the harvesting and transportation of the material, nor the impact of the production of the application. This is covered in the following KPI.

KPI 4.1 Emissions during production of the object - Counterpart of KPI 3.1. Where the first one looks at emissions saved by not using virgin materials, KPI 4.1 analyses “the effect of the use of circular materials and robotic production“. Here, three sources of emissions are distinguished:

1. Harvesting the circular material
2. Transportation of the material to the production site
3. (Robotic) production of the application

What is not considered is the energy needed from post-production, to transport the application to its final use destination.

KPI 6.1 Job creation - This indicator originates from the common (mis)conception that ‘robots will take over human labour’. To analyse the actual impact from robotic production, this indicator calculates the time needed for all activities related to the design and production of the application. This includes time for sourcing, harvesting, and processing of circular materials. The KPI-framework allows for the evaluation of larger numbers of products, spreading one-time indirect activities such as design, planning and management over the production of multiple units.

KPI 8.1 Avoided costs from re-using materials - This indicator looks at the costs saved by not-using virgin materials, without considering costs associated to the harvesting or processing of the circular material. These are covered in the next KPI (9.1).

KPI 9.1 Costs of production - This indicator looks at all costs items, associated to the making of the application. Six cost categories are distinguished: 1. Labour, 2. Material, 3. Energy, 4. Transport, 5. Consumables, and 6. Machines (robots, end-effectors (e.g. milling head), handheld tools). Labour costs are directly associated to KPI 5.1 ’Job Creation’ and thus also include indirect costs for design, planning and management. They also include time spent on harvesting, transporting, and processing of circular wood. Similar to KPI 4.1 ‘Emission’, post-production costs (transport-tation of the application to its final use destination) are not considered.

KPI 9.2 Annual costs for maintenance of the product – Calculation of this KPI is still in its infancy and is not addressed in this paper.

Applying the KPI Framework to the “One Plank” challenge

In 2024, the AUAS Digital Production Research Group (DPRG) together with HMC (Hout en Meubileringscollege) Amsterdam, and Stayokay Dutch Hostels organized two “One Plank” challenges for students of the Minor Robotic Production and Circular Materials, offered at the AUAS Robot Lab. In this challenge, students were to design and make an application for hospitality, each from one identical piece of wood. The wood was harvested from the renovation of the bedrooms of one of the hostels of Stayokay. Every year, Stayokay renovates two of their hostels, implying that this material stream will come

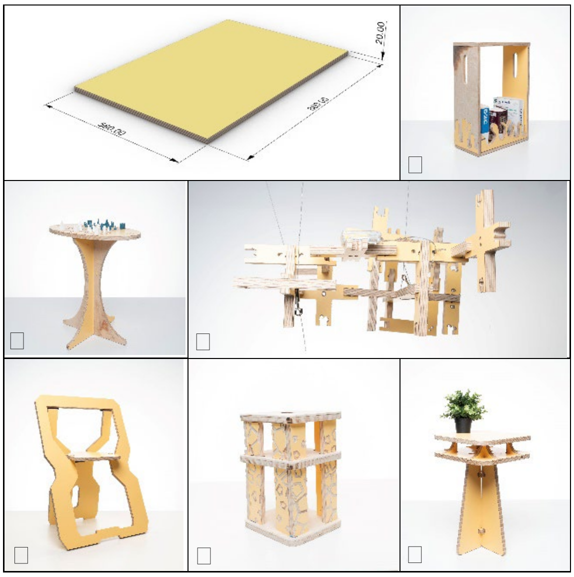

Figure 2. First challenge; the original plywood (top) and the six resulting objects

available continuously during the upcoming years.

In the first challenge, the students were given a rectangular piece of plywood with yellow melamine cover. In the second challenge, they received a bunkbed end board, consisting of two beech poles and two veneer-covered plywood planks. In the first challenge, the focus was on the design and production of a *discrete* object, whereas in the second challenge the students were instructed to design a product *system*, suitable to create a family of objects. Results of the challenges are given in Figure 2 and Figure 3.

During the making of the objects, students were asked to carefully measure all data needed to calculate the KPI’s (e.g. weight of the plank, weight of the object, design time, production time, milling time, etc.). Comparing the KPI’s for six different objects made from the same material can give valuable insights into the impact of robotic production from circular materials.

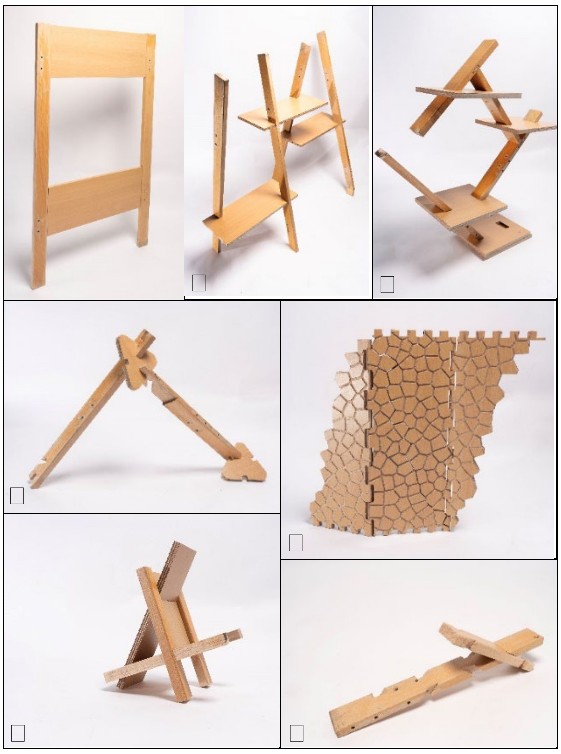

Figure 3. Second challenge: the original bunkbed end board (top, left) and resulting objects

An important difference between the two challenges was, that in first challenge all students worked with the same amount and type of wood, whereas in the second challenge, students selected and used a variable amount and type of wood. Some chose to only use the poles, others focused on the boards. Some used two, or even three poles and boards, others only one element.

Impact analysis

Environmental impact of wood reuse

Reusing waste or left-over wood has a positive impact on the environment, by saving the use of virgin material, thus saving on the harvesting, transportation and processing of trees. Environmental gains are partly offset by the environmental burdens of processing the materials into applications. Figure 4 shows the balance for the first challenge (numbers referring to the objects shown in Figure 2).

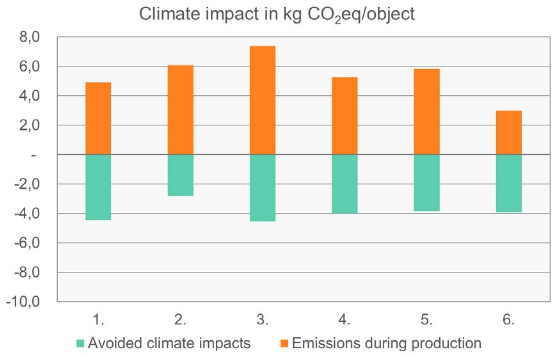

Figure 4. Environmental gains (green) vs. production burdens (red) for the first challenge

From this figure it becomes clear that the gains are the same order of magnitude as the burdens. Reusing waste wood had noteworthy impact.

In the second challenge the relationship between gain and burden is less clear (Figure 5).

The gain strongly depends on the specific amount and type of reused wood. The environmental impact of beech wood (0,17 kg

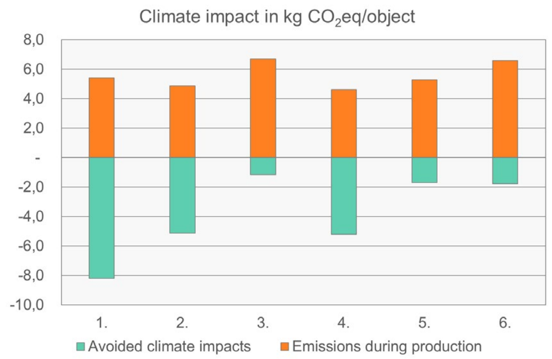

Figure 5. Environmental gains (green) vs. production burden (red) for the second challenge

CO_2eq/kg[1]) is much lower than that of plywood (0,82 kg CO_2eq/kg[1]). Reusing the poles has thus far less environmental gains than reusing the boards. Object 1 reuses three poles and boards, leading to high impact gains, object 6 uses only one pole[2].
From this analysis it becomes clear that the type of waste wood can have a large impact on environmental impact. Determining wood type prior to the harvesting process can help focusing on the materials with the highest impact.

Robotic production costs

In the KPI framework, production costs are calculated using a range of categories. Figure 6 shows the resulting scores broken down into the categories. Within each challenge, there is a range of production costs, related to the complexity of the object. Main cost components are labour costs and robot costs. Both are strongly correlated with production time.

Labour costs are calculated not only from production time, but also from design, pre-, and post-production times, which are not easy to assess without having the total production process and the number of objects produced in mind. Design time per object will decrease as more objects are produced. Moreover, within the environment of the Robot Lab, production is continuously monitored, leading to high estimates of labour costs for production. In a more realistic factory setting, robotic production will run unsupervised, reducing labour costs substantially. Labour costs in the “One Plank” Challenge are thus higher than is to be expected in a factory setting.
Robot costs are calculated using an average CAPEX[3] costs per hour, derived from previous research into the business case of robotic production (Vrutaal et al., 2024). For the main robot used for the challenges, an ABB IRB 2600, these costs are estimated € 27,50 per hour.

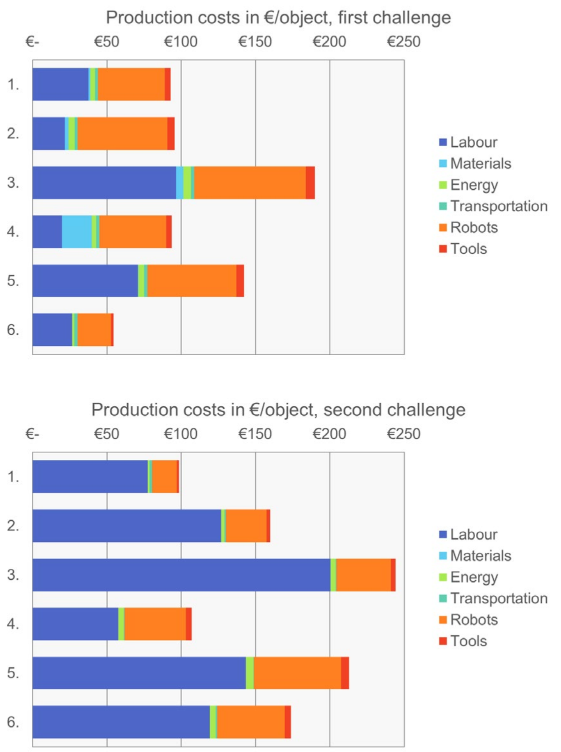

Figure 6. Production costs breakdown for first challenge (top) and second challenge (below)

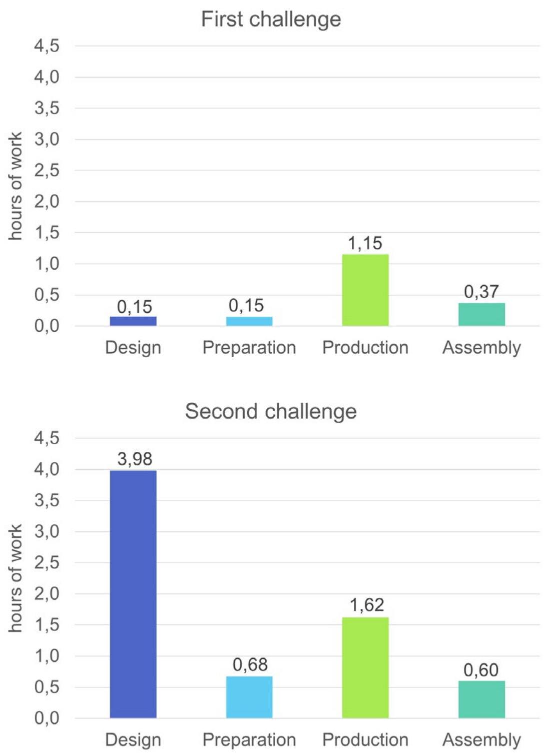

Figure 7. Breakdown of hours of work (average per challenge)

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[1] Data from Ecoinvent (2024)
[2] The low gain score for object 5 is unclear, it is assumed to be a calculation error
[3] Capital Expenditure, i.e. depreciation costs of the robot

In a real production settings, robot use costs will be substantially higher, since they will include OPEX[4] in the costs per hour. Comparing the first and the second challenge, the results shown in Figure 6 indicate that the main cost difference is caused by labour costs.
Figure 7 shows the related breakdown of underlying hours of work in the four categories (Design, Preparation, Production and Assembly). Clearly, in the second challenge more time was spent on design. This was partially caused by the specific question to create a (parametric) system from multiple pieces of wood, more than to design and make just one discrete object.
Overall, from this KPI it becomes clear that production time is key to create economically feasible applications from waste wood. Both the human time and robotic time should be addressed. Human time could be reduced by developing stand-alone production set-ups which do not need supervision. Robotic time could be reduced by optimizing toolpaths, increasing milling speed and working with multiple clamping stations to avoid idle time, when different robots are working together.

Conclusions and Outlook

Wood is an increasingly demanded renewable resource and an important raw material for construction and materials. Demands are thus rising, with a growing attention for re-use and upcycling. To assess the impact of waste wood re-use and upcycling for applications such as furniture, interiors and buildings, a framework of indicators was defined and developed. Applying this framework to the actual digital design and production of a range of applications from circular wood, shows how the framework can be used to compare series of different applications, towards finding out where the main drivers are to enhance the uptake of robotic production with circular materials. In the case of the "One Plank" Challenge, main findings are:

- The environmental gains of using waste wood are of the same order of magnitude as the environmental burdens of the robotic production of connected applications. Wood upcycling has noteworthy impact.
- The environmental gains of using waste wood can strongly vary, depending on the type of wood used. Determining wood type during the harvesting process can help focusing on the materials with the highest impact.
- Production time is key to create economically feasible applications from waste wood. Both the human time and robotic time should be addressed.

For further developments, the following lines are being pursued:

1) Developing the KPI-framework into a more advanced design tool that integrates impact calculation into parametric design software, to allow changes in the design of a circular application to be immediately reflected a "dashboard" summarizing impact score.
2) Connecting the KPI-framework to digital twin software for robotic production (Tao et al., 2019), in which various production set-ups can be simulated. This will allow for further optimization of production costs, one of the main cost components of robotic production.
3) Expanding the KPI-framework to incorporate other materials and production technologies into a more generic tool for impact evaluation for circular applications.

Acknowledgments

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[4] Operational Expenditure associated to robot use, i.e. maintenance, energy use, space rent, indirect staff

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