The Circular Wood KPI-framework

Assessing and managing the (sustainability) performance of waste wood upcycling applications

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The 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. This opens opportunities for new business models, empowered by the use of digital design and technologies. A KPI-framework has thus been developed to assess the impact of waste wood upcycling, to provide new business perspectives. It is conceived as a tool to enable circular businesses to select the most appropriate circular wood applications for their portfolio. The framework currently consists of eight indicators addressing circularity, environment, society and economics. This paper presents these indicators and shares insights for further development and enhancement of the framework.

Keywords

Upcycling, wood, digital design, robotic production, impact

Introduction

Wood is a valuable and sustainable material within the circular and biobased economy, because it has the opportunity to store CO_2 if grown and harvested correctly (Szulecka, 2019; Woodard & Milner, 2016). Consequently, construction, interior architecture 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 used 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, Gold & Bocken, 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).

An important strategy to create value from waste and residual wood is the use of digital design and robotic production technologies, as these are especially suited for generating innovative concepts and applications 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 (De Siqueira, Malaj & Hamdani, 2022). 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 (Vogtländer, 2014; Siebert et al., 2018) or material flow analysis (Brunner & Rechberger, 2016). Yet these tools do not cover all aspects, and are not specifically focussed on circular wood use. Moreover, a scientific approach as 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. The aim here is to combine existing tools, making them accessible and adding new indicators into one integral framework which enables circular wood businesses to select the most appropriate applications and business models for their portfolio. The developed KPI-framework 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 research approach, describes the integral framework ("KPI-framework") and discusses specific points for further development. This includes more detailed evaluations, expanding the framework from circular wood to other upcycling endeavours, and broadening it from robotic wood manufacturing to other production technologies (such as 3D printing).

Research approach

A Key Performance Indicator, or KPI, is a measurable value (which can be both quantitatively or 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)[1], coordinated by the Digital Production Research Group (DPRG)[2] of the Amsterdam University of Applied Sciences. The framework can be used as a tool for the evaluation and comparison of specific applications from waste wood.

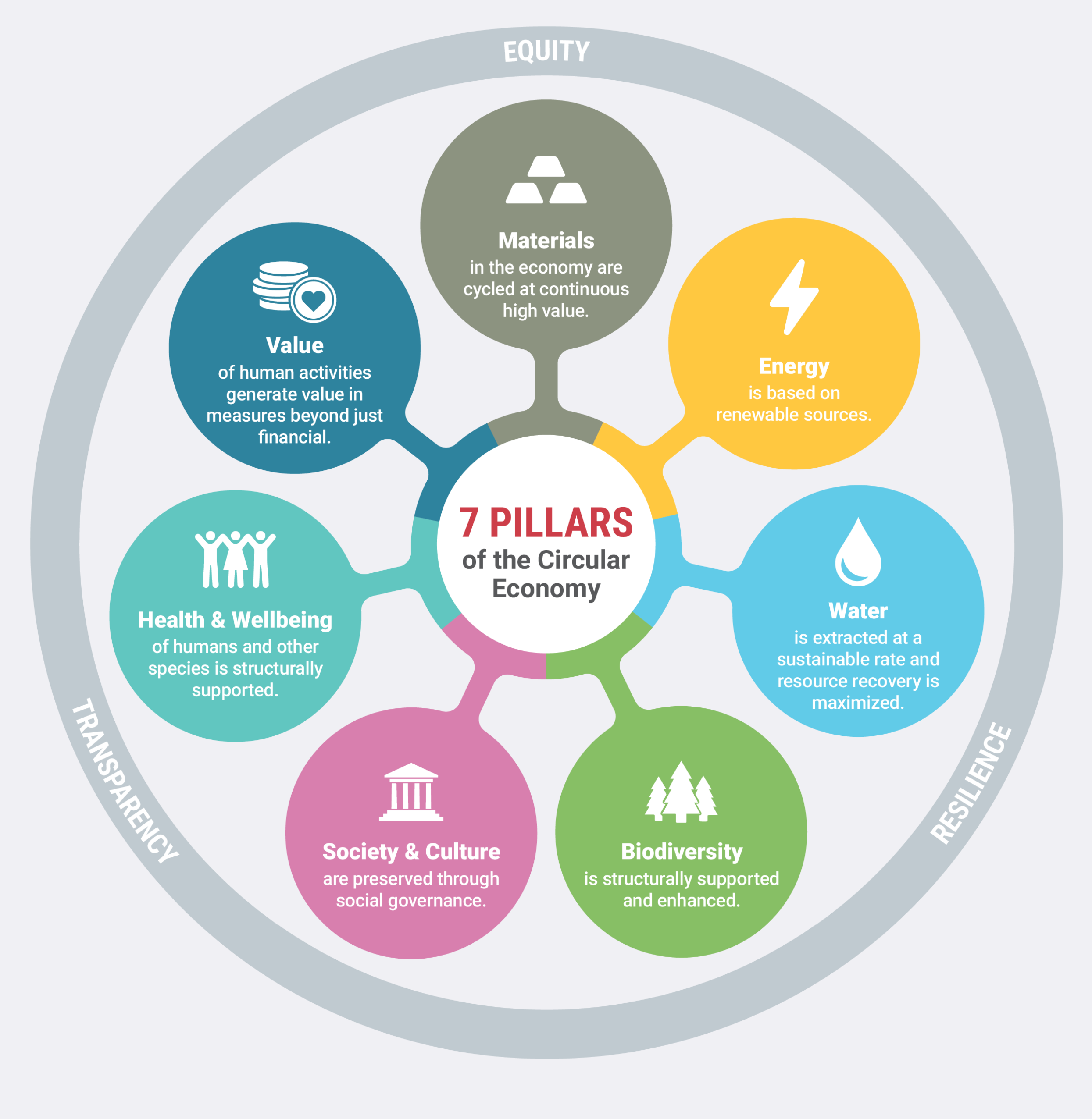

Fig. 1 The 7 pillars of the Circular Economy (©Metabolic)

As a starting point, the ‘seven pillars of the circular economy’ model of Metabolic (Anon, 2019) and the Donut Economy model of Kate Raworth (Raworth, 2017) were used. In a series of workshops with all partners of the aforementioned CW4N project (representatives from housing corporations, construction industry, wood industry and the municipality of Amsterdam) and guided by circularity researchers from AUAS and Metabolic, a longlist of 20 quantitative indicators in four categories (material management, environmental, socio-cultural and economic) and in three lifecycle phases (design, use and end-of-life) was drafted from the models mentioned above. For each of the indicators, a definition and calculation method was created. This longlist was then condensed to a set of eight indicators, which were the most relevant to the project stakeholders.

The KPI-framework

KPI-framework overview

The current KPI-framework is a set of eight indicators, derived from a total of twenty (see Table 1), which can be used to analyze 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) is benchmarked with a reference application (e.g. a comparable, standard IKEA stool).

Table 1 Overview of 20 Circular Wood Key Performance Indicators (bold= the selected 8)	
Material Management	
1. Reused material	**% of the product that consists of locally harvested wood [KPI 1.1]**
	% of wood that is retained at its highest complexity
	% of material that is wasted during production process
	% of waste wood of housing corporations
2. Circularity potential	**% of components which can easily be reused at the end of function with the use of digital production (computational design and robotic production) [KPI 2.1]**
	End of function potential
Environmental	
3. Avoided impacts	**Avoided embedded impact from avoided virgin materials (Hardwood, Other wood, Plastic, Metal, Other) [KPI 3.1]**
	Avoided emissions from incineration of wood

4. Created impacts	**Emissions during production of product [KPI 4.1]**
	Expected yearly emissions during use & maintenance
	Expected emissions and impacts at end of function
	# Wood contaminated with toxic materials during the production process
Socio-cultural	
5. Job creation	**(local) Jobs created (high and low educated) [KPI 5.1]**
6. Meaningful applications	% of end user design criteria met by design
	Overall satisfaction from end-user with product
7. Knowledge development	# new applications of waste wood suitable for decentralized production techniques
	# of people that have been in contact with circularity principles thanks to the initiative
Economic	
8. Avoided costs	**Avoided costs of virgin material use [KPI 8.1]**
	Avoided costs of wood disposal
9. Created costs	**Production costs [KPI 9.1]**
	Costs for maintenance and operation or the product [KPI 9.2]

To calculate the indicators, validated models, databases and calculation methods were used, where available. The actual calculation is performed in an excel model, built and designed with a dashboard to visually summarize the scores. This visual presentation is important, to facilitate that the framework can used for decision-making processes in multiple domains. To test the functionality of the KPI-framework, starting in 2021, three different circular wood designs were evaluated: a reception desk, a coffee table, and a room divider. Resulting scores are presented in table 2. It should be noted that these calculations were used for the development of the framework, leading to some methodological changes between the three cases. The presented results must thus be considered preliminary.

Table 2 Preliminary impact assessment of three circular wood applications

Application KPI	Johan Cruyff ArenA reception desk[3]	Coffee table[4]	Room divider[5]
1.1 reused material percentage	99%	100%	96%
2.1 circularity potential	95%	100%	98%
3.1 avoided impacts	29,2 kg CO_2eq € 8,85 (eco-costs)	1,5 kg CO_2eq € 0,27 (eco-costs)	6,8 kg CO_2eq € 1,20 (eco-costs)
4.1 emissions during production	91,8 kg CO_2eq	1,0 kg CO_2eq	2,3 kg CO_2eq
5.1 job creation	669 hrs	7 hrs	24 hrs
6.1 avoided costs of virgin material use	€ 1.148	€ 27	€ 120
9.1 production costs	€ 28.701	€ 155	€ 798
9.2 maintenance costs	Calculation method not yet available		

In the next sections, the eight indicators and the benchmarking process are discussed in more detail.

Benchmarking

The KPI-framework allows for performances to be calculated. Yet, without a benchmark, these performances remain meaningless. For example, one may calculate the robotic production of the Johan Cruyff ArenA reception desk as 669 hours of work (indicator 5.1 ‘Job creation’ in table 2), yet this remains meaningless, unless it is compared to a reference case. With this purpose, we used the Rechtbank Zwolle reception desk from the same designer and manufacturer (Nijboer Interieur & Design), which required an estimated 200 hrs of work (using conventional production methods). In this way we can compare robotic to conventional production and conclude that in the case of the Johan Cruyff reception desk -produced as a research prototype- much hand work was required. The calculation sheet of this indicator gives further details for analysis, as shown in table 3.

Table 3 Benchmarking the KPI 5.1 score ‘job creation’ (details from calculation sheet)

Circular application: Johan Cruyff ArenA reception desk		Reference object: Rechtbank Zwolle reception desk	
activity	time in hrs	activity	time in hrs
Wood harvesting	8	Projectmanagement	28

Other material sourcing	16	Engineering	45
Production at Robot Lab:		Production at Nijboer:	
Material research	40	Machining	14
Material reception	40	Production/assembly	60
Robot programming	75		
Robot operation	50		
Montage on-site	320	Montage on-site	55
TOTAL	**669**		**202**

Benchmarking helps comparing calculations, however it creates two problems. First, it is not always possible to find a reference case similar to the circular wood application. In the case of the reception desk, the desk of the Rechtbank Zwolle is not composed of the same materials. Similarity here exists only in terms of size, quality and appearance, the latter two being largely subjective criteria.

Second, the data from reference products or applications are not always easily available. As an example, we can come up with the impact assessment of the second case in table 2. This case consists of a coffee table, composed from the wood of a waste front door. By coincidence, a comparable table was found in the catalogue of the furniture company Linteloo. Unfortunately and despite our attempts, the required data from the reference object was not provided.

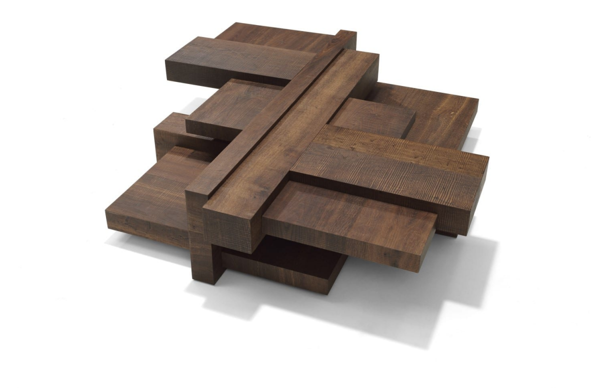

Fig. 2 Coffee table case study (left, ©DPRG) and benchmark furniture item, the *Manhattan* table from Linteloo (right, ©Linteloo)

This problem might be overcome by creating relative KPI scores, which help relate all scores to a common denominator (e.g. the weight of the object as illustrated in table 4 below). In this way different circular wood cases can be compared without a benchmark, even if they have quite different sizes.

Table 4 Comparing impacts: calculating KPI-scores per kg

Application	Johan Cruyff ArenA reception desk	Coffee table	Room divider
KPI			
Object weight	*278 kg*	*9 kg*	*42 kg*
1.1 reused material percentage	99%	100%	96%
2.1 circularity potential	95%	100%	98%
3.1 avoided impacts **per kg object**	0,11 kg CO_2eq € 0,032 (ecocosts)	0,17 kg CO_2eq € 0,030 (ecocosts)	0,16 kg CO_2eq € 0,029 (ecocosts)
4.1 emissions during production **per kg object**	0,33 kg CO_2eq	0,11 kg CO_2eq	0,05 kg CO_2eq
5.1 job creation **per kg object**	2,41 hrs	0,78 hrs	0,57 hrs
6.1 avoided costs of virgin material use **per kg object**	€ 4,13	€ 3,00	€ 2,86
9.1 production costs **per kg object**	€ 103	€ 17	€ 19

This approach will not work if other applications -not made with circular wood- are included in the comparison, like objects from (heavy-weight) cocrete (which will lead to much lower levels of job creation *per kg object*) or (light-weight) plastics (which will lead to much higher levels of job creation *per kg object*). These comparisons, 'contaminated' with non circular wood examples, will be rather meaningless.

Reused material percentage (KPI 1.1)

In the original staging of the KPI's, this indicator was defined as "percentage of the product that consists of locally harvested wood". Yet during development, it felt unfair to look exclusively at the reuse of locally harvested wood. Besides it should be acknowledged that many other materials consist of recycled content. Therefore, when comparing a bookshelf from harvested waste wood with a new BILLY bookshelf from IKEA, the calculation should take into account that BILLY is made from particle board, which can consist of more than 50% of waste wood (Vis, Mantau & Allen, 2016). Given this, the calculation of this indicator now considers both aspects: the re-use of waste material and the use of recycled content.

Moreover, it should be noted that this indicator looks at material on a product level. Thus it does not take into account material loss during production.

Circularity Potential (KPI 2.1)

The definition of this indicator is: the percentage of the application that can be easily re-used at the end of its current life cycle. There are various methods to calculate this indicator. One is the elaborate ’Circular Product Design Assessment’ methodology developed in the EU-funded ResCoM (Resource Conservative Manufacturing) research project (Asif, Lieder & Rashid, 2016). This methodology is based on the analysis of the material composition of a given application, how easily this application can be repaired or its parts be replaced (’hotspot mapping’) and how well the application can be upcycled at its end-of-life at what R-levels (Reuse, Repair, Remanufacture, Recycle, etc.) (Potting et al., 2018). The analysis results in a circularity score, which could directly be used in the KPI-framework.

Alternatively, there is the releasability index (”losmaakbaarheidsscore”) which only focuses on how the individual parts of the application can be taken apart again (van Vliet, van Grinsven & Teunizen, 2019). In this index, form-based connections have a high score, while chemical bonding connections consequently have a low score. All connections can thus be evaluated, resulting in an average score for releasability. Table 5 gives an overview of the score for various connection types.

Table 5 Releasability score for different connection types

Type of connection		score
Dry connection	Interlocking connection	1,00
	Click connection	1,00
	Velcro connection	1,00
	Magnetic connection	1,00

Connection with added elements	Nut and bolt connection	0,80
	Spring connection	0,80
	Corner connection	0,80
	Screw connection	0,80
	Other added elements	0,80
Direct integral connection	Pin-connection	0,60
	Nail connection	0,60
Soft chemical connection	Water glue connection	0,20
	Foam connection (PUR)	0,20
Hard chemical connection	Chemical glue connection	0,10
	Poured connection	0,10
	Welded connection	0,10
	Cement connection	0,10
	Chemical anchor	0,10
	Hard chemical connection	0,10

In the KPI-framework, it was decided to use this second calculation method, although looking only at releasability may be a bit too limited. Re-useability (at different R-levels) is also determined by the shape of components, the material they are composed of, the likelihood of failure or damage, etc. Further discussion is needed on how to incorporate these aspects in the score, which would affect this indicator.

Avoided impacts (KPI 3.1)

This indicator analyses “the avoided environmental impact of using circular wood, instead of harvesting and applying virgin wood“. To calculate this indicator, data from the ecoinvent database is used[6]. This database contains embedded CO_2 equivalents[7] and eco-costs[8] associated with the specific type of wood. An important factor in this data is the end-of-life scenario. The ecoinvent database uses three scenarios: landfill, waste treatment & open loop recycling, and closed loop recycling & cofiring. If we would apply the last scenario, using virgin wood would incorporate negative CO_2eq values due to energy recovery from burning the wood after its use. Given that circular wood might also be burned after its use, the conclusion is that using virgin wood will not lead to additional negative CO_2 emissions due to energy recovery, assuming that the circular wood is of the same type as the virgin wood.

The avoided impacts should thus concentrate on the impact of wood harvesting, shipping and processing only: by re-using waste wood instead of virgin wood, we avoid the need to harvest this virgin wood, as well as its shipping and processing. We also do not take into account that using virgin wood might lead to changes in CO_2 storage in forests, assuming that the forest where the wood is harvested from is a stable ecosystem, as described in (Vogtlander, van der Velden & Lugt, 2014).

Finally, this indicator looks only on the material level. It does not consider the environmental impacts related to the harvesting and transportation of the circular wood, nor the impact of the production of the final application. This is covered in the following KPI.

In short, this indicator only clarifies how much impacts are avoided on the material level, by re-using waste wood instead of the same type of virgin wood.

Emissions during production of the object (KPI 4.1)

This indicator is the 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 wood and robotic production“. Here, three sources of emissions are distinguished:

0. Harvesting the waste wood
0. Transportation of the waste wood to the production site
0. (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.

In the current KPI-framework, the CO_2eq value is calculated. In future revisions, given that the attention for raw material depletion is growing, it might be better to replace the emissions-score by the eco-costs score (which takes material depletion into account).

Job creation (KPI 6.1)

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. In the case of circular wood, this includes time for sourcing, harvesting, and processing of waste wood. 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.

Avoided costs from re-using materials (KPI 8.1)

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). To calculate this KPI, for all circular materials used in the application, costs for the same virgin, non-circular, materials are surveyed. During the development of the KPI-framework (in 2021), it was assumed that the circular materials were harvested from waste, without value. Over time, it has become clear that circular materials can have market value and are not available free of charge. In this KPI, this is be taken into account.

Costs of production (KPI 9.1)

This indicator looks at all costs items, associated to the making of the application. Six cost categories are distinguished:

- Labour costs
- Material costs
- Energy costs
- Transport costs
- Consumables / Tooling
- Machine costs

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 (transportation of the application to its final use destination) are not taken into account.

Annual costs for maintenance of the product (KPI 9.1)

This KPI must still be detailed. It should be noted that the KPI-framework so far has been used for indoor furniture applications only, with very low costs for maintenance. When moving to constructive building components or to outdoor structures from circular wood, maintenance and repair will become a more important factor to consider during design. This KPI then should include costs for painting and repair of wooden parts. Here, robotics can facilitate design for disassembly strategies by producing custom joints for easy replacement.

Discussion

Some discrepancies can be noted in the overall framework. Some indicators are easy to understand and seem to be well defined to tell the story of circular wood (”The Johan Cruyff ArenA for 99% is composed of waste wood, saving € 1.148 of new wood”). Other indicators though, such as the total production costs, are more complex to calculate and may too broadly try to cover all aspects related to the specific KPI.

Moreover, not all indicators use the same system boundaries. Some indicators focus on the product itself (e.g. KPI 1.1 ’Material reuse’, neglecting the waste of circular wood during robotic production), others incorporate the harvesting, transportation and production (e.g. KPI 4.1 ’Emissions during production’), which are essential processes when using circular wood. It might be better to unify the system boundaries for all indicators, though this will make some of them less easy to calculate, especially when using a reference object for benchmarking. If harvesting, transportation, and pre-production processing of circular wood are considered, this should also be the case for the virgin materials of the benchmark case, though for these materials the data related to harvesting, transportation and pre-production might not easily be available.

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 series of indicators were defined and developed. For the calculation of impact scores, various models, databased and methods are integrated. This is *work in progress*, with still many details to be discussed and issues to be resolved (e.g for the KPI 2.1 ‘Circularity Potential’ score). In particular, not all indicators use the same system boundaries. Moreover, the use of reference objects for benchmarking is under discussion.

Following the above reflection, future work will concentrate on resolving these issues. Three lines of development may be pursued:

0. Developing the KPI-framework into a more advanced design tool that integrates impact calculation into parametric design and production software, in order to allow changes in the design of a circular application to be immediately reflected in the KPI-framework score.
0. Enhancing the KPI-framework with additional / updated / more robust calculation methods.
0. Expanding the KPI-framework to incorporate other materials and production technologies (for example 3D-printing with biobased materials).

Acknowledgement

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References

Anon (2019) *The Seven Pillars of the Circular Economy*. 2019. https://www.metabolic.nl/news/the-seven-pillars-of-the-circular-economy/ [Accessed: 10 February 2023].

Asif, F.M.A., Lieder, M. & Rashid, A. (2016) Multi-method simulation based tool to evaluate economic and environmental performance of circular product systems. *Journal of Cleaner Production*. 139, 1261–1281. doi:https://doi.org/10.1016/j.jclepro.2016.08.122.

Besserer, A., Troilo, S., Girods, P., Rogaume, Y. & Brosse, N. (2021) Cascading Recycling of Wood Waste: A Review. *Polymers*.13 (11). doi: https://doi.org/10.3390/polym13111752.

van Bruggen, R. & van der Zwaag, N. (2017) *Knelpuntenanalyse houtrecycling*.

Brunner, P.H. & Rechberger, H. (2016) *Handbook of Material Flow Analysis : For Environmental, Resource, and Waste Engineers, Second Edition*. doi:https://doi.org/10.1201/9781315313450.

Gohar, L.K. & Shine, K.P. (2007) Equivalent CO2 and its use in understanding the climate effects of increased greenhouse gas concentrations. *Weather*. 62 (11), 307–311. doi:https://doi.org/10.1002/wea.103.

Jonsson, R., Blujdea, V.N., Fiorese, G., Pilli, R., Rinaldi, F., Baranzelli, C. & Camia, A. (2018) Outlook of the European forest-based sector: forest growth, harvest demand, wood-product markets, and forest carbon dynamics implications. *iForest - Biogeosciences and Forestry*. 11 (2), 315–328. http://www.sisef.it/iforest/contents/?id=ifor2636-011.

Lüdeke-Freund, F., Gold, S. & Bocken, N.M.P. (2019) A review and typology of circular economy business model patterns. *Journal of Industrial Ecology*. 23 (1), 36–61.

Malé-Alemany, M., Schoen, T., Galli, M., Bors, V., Kozhevnikova, A. & Dijk, L. Van (2022) *“ Once my front door – now my coffee table ”; Advanced computational design and robotic production with waste wood*.pp.1–5.

Potting, J., Hanemaaijer, A., Delahaye, R., Hoekstra, R., Ganzevles, J. & Lijzen, J. (2018) *Circulaire economie: wat we willen weten en kunnen meten - systeem en nulmeting voor monitoring van de voortgang van de circulaire economie in Nederland*.

Raworth, K. (2017) *Doughnut economics: seven ways to think like a 21st-century economist*. Chelsea Green Publishing.

Siebert, A., Bezama, A., O’Keeffe, S. & Thrän, D. (2018) Social life cycle assessment indices and indicators to monitor the social implications of wood-based products. *Journal of Cleaner Production*. 172, 4074–4084. doi:https://doi.org/10.1016/j.jclepro.2017.02.146.

De Siqueira, G., Malaj, S. & Hamdani, M. (2022) Digitalization, Participation and Interaction: Towards More Inclusive Tools in Urban Design—A Literature Review. *Sustainability*.14 (8). doi:https://doi.org/10.3390/su14084514.

Szulecka, J. (2019) Towards Sustainable Wood-Based Energy: Evaluation and Strategies for Mainstreaming Sustainability in the Sector. *Sustainability*.11 (2). doi:https://doi.org/10.3390/su11020493.

Vis, M., Mantau, U. & Allen, B. (2016) *CASCADES: Study on the Optimised Cascading use of Wood*. Publications Office.

van Vliet, M., van Grinsven, J. & Teunizen, J. (2019) *Circular Buildings – een meetmethodiek voor losmaakbaarheid, versie 1.1*.

Vogtländer, J. (2014) *LCA - a practical guide for students, designers and business managers*. Delft Academic Press.

Vogtlander, J., Mestre, A., R, V., Scheepens, A. & Wever, R. (2013) *Eco-efficient value creation; sustainable design and business strategies*.

Vogtlander, J., van der Velden, N.M. & Lugt, P. (2014) Carbon sequestration in LCA, a proposal for a new approach based on the global carbon cycle; Cases on wood and on bamboo. *The International Journal of Life Cycle Assessment*. 19. doi:https://doi.org/10.1007/s11367-013-0629-6.

Woodard, A.C. & Milner, H.R. (2016) 7 - Sustainability of timber and wood in construction. In: J.M.B.T.-S. of C.M. (Second E. Khatib (ed.). *Woodhead Publishing Series in Civil and Structural Engineering*. Woodhead Publishing. pp. 129–157. doi:https://doi.org/10.1016/B978-0-08-100370-1.00007-X.

Footnotes

0. : www.cw4n.nl ↩
0. : https://www.hva.nl/kc-techniek/gedeelde-content/hoofddocentschappen/digital-production-research-group/dprg.html ↩
0. : www.regieorgaan-sia.nl/taskforce-applied-research-sia/a-vip-reception-desk-made-of-waste-wood/ ↩
0. : www.cw4n.nl/case-study-1/ ↩
0. : www.cw4n.nl/case-study-3/ ↩
0. The ecoinvent Database is a Life Cycle Inventory (LCI) database that supports various types of sustainability assessments. It is a repository covering a diverse range of sectors on global and regional level. It currently contains more than 18’000 datasets containing information on the industrial or agricultural

process they model, measuring the natural resources withdrawn from the environment, the emissions released to the water, soil and air, the products demanded from other processes (electricity), and the products, co-products and wastes produced (www.ecoinvent.org/the-ecoinvent-database/). ↩

0. A carbon dioxide equivalent or CO_2 equivalent, abbreviated as CO_2eq is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential **(Vogtlander et al. 2013)**. ↩

0. Eco-costs are the costs of the environmental burden of a product on the basis of prevention of that burden. They are the costs which should be made to reduce the environmental pollution (carbon footprint, eco-systems costs and human health costs) and materials depletion in our world to a level which is in line with the carrying capacity of our earth **(Vogtlander et al. 2013)**. ↩