Rhino*Circular*: Development and Testing of a Circularity Indicator Tool for Application in Early Design Phases and Architectural Education

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Rhino*Circular* is a CAD plugin developed within the Circular Construction Lab (CCL) at Cornell University that assesses a building design's environmental impact in respect to its embodied carbon values and *circularity*: the degree to which design solutions minimize extraction and waste in favor of reusable, recyclable and renewable material resources. Over their full life cycle, current buildings account for 39% of carbon dioxide emissions [1] and more than 50% of resource extraction and solid waste production. [2,3] As a way to overcome the social, economic, and environmental problems of this linear economic system, the concept of the circular economy is increasingly gaining attention. Activating the built environment as a material reserve for the construction of future cities would not only provide valuable local resources, but also potentially prevent up to 50% of the industry's emissions by capitalizing on embodied carbon. [1] However, this requires radical paradigm shifts in how we design and construct buildings (e.g. materials selection/ design for disassembly), and in how resources are managed within the built environment. Buildings and regions need to anticipate stocks and flows of materials, documenting and communicating which materials in what quantities and qualities become available for reuse or recycling where and when. Rhino*Circular* allows direct and immediate feedback on design decisions in respect to formal deliberations, structural considerations, material selection and detailing based on material passports and circularity indicators. It can be integrated in existing and complex workflows and is compatible with industry standard databases while providing its own essential dataset complementing missing information.

INTRODUCTION

Globally, the construction industry is the biggest consumer of energy and materials. Over their full life cycle, buildings account for 39% of carbon dioxide emissions [1] and more than 50% of resource extraction and solid waste production.[2, 3] As a way to overcome the social, economic, and environmental problems of the current linear economic system, the concept of the circular economy (CE) is increasingly gaining attention. A CE has been defined as "…one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times."[4] The consequent closing of production and consumption loops offers not only the possibility to end the loss of valuable finite resources, but also to reduce dependencies on global, volatile resource markets, prevent greenhouse gas emissions, mitigate the effects of the climate crisis, and support new business models and green job opportunities.[5, 6]

Since rates of construction are significantly higher than demolition and discard, society is building up an important economy-wide anthropogenic material stock.[7] Today, the amount of many metals and minerals bound within the built environment has already outgrown their respective naturally occurring reserves.[8] By some estimates, existing buildings account for as much as 90% of all materials ever extracted,[9] hastening calls for the development of technologies and strategies for circular resource utilization. Additionally, as global and local actors seek to address climate concerns the implicit value associated with embodied carbon, labor, knowledge and water can impact material valuation going forward. The loss of this significant existing stock of materials and the related embodied values due to the current practice of demolition and landfilling will consequently no longer be viable practically, environmentally, or economically.

Activating the built environment as a material reserve for the construction of future cities would not only provide valuable local resources, but also potentially prevent up to 50% of the industry's emissions by capitalizing on embodied carbon.[1] However, this requires radical paradigm shifts in how we design and construct buildings (e.g. materials selection/ design for disassembly), and in how resources are managed within the built environment. Buildings and regions need to anticipate stocks and flows of materials, documenting and communicating which materials in what quantities and qualities become available for reuse or recycling where and when. The current waste of resources is facilitated by the absence of such relevant data on materials: Historically, the construction industry has not documented the stocks, flows, specifications, and values of building materials and components over time, nor has it prepared this data for future use. In business, what gets measured gets managed, so the availability and utilization of this data represent one of the keys to developing material loops critical to the CE.

Efforts by a number of organizations over the last ten years in creating and making available such data have offered several different approaches, each with their advantages and shortcomings. While top-down approaches focus on macro-economic statistics as information source, bottom-up approaches extrapolate urban material stock and flow information based on a combination of indicators such as the material composition of typical buildings and floor surface area. As an example, the TABULA project by Intelligent Energy Europe surveyed existing buildings and compared them to one of several building types, organized regionally, in order to enable estimation of the material stock in the already-built environment.[10] Expanding on this methodology, a study of the city of Chiclayo, Peru, used Google Street View and municipal cadasters (legal registers of property boundaries and value) as an efficient means to survey the city's residential sector.[11] Most recently, several studies combined bottom-up approaches with geographical information systems (GIS) and airborne light detection and ranging (LiDAR) data as additional indicators to estimate the building stock of Esch-sur-Alzette (FR), Luxembourg City (LU), Atlanta (US), Melbourne (AU), Beijing (CH), Odense (DK), and Ithaca (US).[12-17]

The emerging concept of materials passports (MP) offers a technical solution to the missing building data documentation, by providing digital twins of buildings, containing detailed inventories of materials and products used, as well as their specifications, location and connection details. Efforts by Madaster, BAMB or EPEA in Europe offer platforms for storing such comprehensive information about materials, often integrating building information modeling (BIM) as the source for volume calculations. As a case-in-point, the Urban Mining and Recycling (UMAR)[18] Unit by Werner Sobek, Dirk E. Hebel and Felix Heisel within the Empa NEST in Dübendorf, Switzerland, was designed and constructed as a fully circular prototypology,[19] achieving a 96% circularity rating[20] on the Madaster platform - the highest of any known building registered on the platform so far.

However, the broad application of MPs to date is restricted by several conceptual and technical limitations: Firstly, MP generation until now has been largely concentrated on the documentation of newly constructed buildings, consequently missing out on two important phases of the building use cycle: 1) The already existing building stock including the aforementioned - so far undocumented - material stock / urban mine, as well as 2) the early design phase where MP thinking and integration could play a significant role in both closing the current supply / demand mismatch of reusable materials and transforming new constructions into the material depots (rather than the urban mines) of the future. A consequent standardization and central registration of MPs covering all buildings and components of the built environment in material cadasters will be a prerequisite for the circular management of resources.

Secondly, while the calculation methods for circularity indicators (CI) have been established in the past years (see method sections below), the underlying and necessary data points are still mostly unavailable to date. Many material flow calculations are missing information especially towards the end-of-use phase of buildings and thus complicate scientific analysis of design decisions. In the case of UMAR, MP creation required building substantial databases of custom materials. Such work is at best tedious, and at worst prohibitively time-consuming for smaller firms, individual designers, and students, assuming the necessary data points can even be found readily. Additionally, while such an approach might be suitable to record what configured materials happen to be reusable in an already-planned building, it cannot provide the necessary feedback to the design decisions themselves and thus does not represent a fundamental shift away from the linear, exploitative thinking that is one root cause of the global resource predicament.

This paper describes the development of a new tool addressing these challenges. Rhino*Circular* is a Rhino3D / Grasshopper plugin developed within the Circular Construction Lab (CCL) at Cornell University, that allows a direct and immediate feedback on design decisions in respect to formal deliberations, structural considerations, material selection and detailing based on MPs and CIs. It can be integrated in existing and complex workflows and is compatible with industry standard databases while providing its own essential dataset complementing missing information. The following paragraphs will highlight the metrics and functionality of the tool for application in architectural design studios, research projects, as well as architectural practice.

RHINO*CIRCULAR*

Rhino*Circular* is a CAD plugin that assesses a building design's environmental impact in respect to its embodied carbon values and *circularity*: the degree to which design solutions minimize extraction and waste in favor of reusable, recyclable and renewable material resources. Embedded into the Grasshopper environment of the popular design software Rhinoceros3D, the tool consists of several components that can be combined or connected through 'visual' scripting to suit the specific needs of a proposed project in any design phase or on any level of detail. The open structure further allows the seamless integration of Rhino*Circular* components into existing workflows, be they sequential, generative, parametric or automated.

Aiming to support a holistic approach to operational and embodied carbon analyses and trade-off strategies on the building and urban scale, Rhino*Circular* interacts with climate and energy simulation workflows such as ClimateStudio[21] or AutoZoner,[22] as well as geometry automation tools such as AutoFramer.[23] The software is further compatible with the industry standard databases such as Madaster or EC3 by offering components to read materials and write MPs into specific portfolios using available application programming interfaces (API). In order to allow the intended seamless exchange of data within such a generative design and simulation environment, the authors are currently also part of a team developing a comprehensive data set, namely BuildingRepo,[24] a forthcoming open-source building repository available online and through its own Grasshopper plugins.

CIRCULARITY INDICATORS

The CI itself is a number between 0 and 1 calculated via a set of equations from parameters such as lifespan, efficiency of recycling, and fraction of feedstock taken from renewable, recycled, or reused sources. The equations were first developed by the Ellen MacArthur Foundation in 2016,[25] and further adapted for their specific application in the built environment by Madaster in 2018.[26] For their application within Rhino*Circular*, certain variables are computed directly from Nurbs and mesh geometry. As summarized in Table 1, values of interest can be organized into three categories: basic parameters provided directly by the user or the respective material database, computed parameters which can be written in terms of the basic parameters, or metrics computed from a combination of basic and computed parameters. Values are further organized by the period of the building's use-cycle analysis to which they pertain: construction, use, or end-of-use phases.

	Basic Parameters	Computed Parameters	Metrics
Construction	F_R = fraction of feedstock recycled by mass F_{RR} = fraction of feedstock rapidly renewable by mass F_U = fraction of feedstock reused by mass M = product mass E_F = efficiency of recycling	$W_F = M(1 - E_F)F_R / E_F$ mass of waste from recycling feedstock $V = M(1 - F_R - F_{RR} - F_U)$ mass of materials from virgin sources	$CI_{construction} = F_R + F_{RR} + F_U$ circularity indicator: construction
Use	L = potential lifespan (yrs) L_{av} = industry average lifespan (yrs)		$CI_{use} = L/L_{av}$ circularity indicator: use
End-of-Use	C_R = fraction of materials recyclable E_C = efficiency of recycling process C_U = fraction of materials reusable	$W_C = M(1 - E_C)C_R$ mass of waste from recycling at end-of-use $W_0 = M(1 - C_R - C_U)$ mass of unrecoverable waste going to landfill, waste-to-energy, etc. $W = W_0 + (W_F + W_C)/2$ total mass of waste	$CI_{end-of-use} = C_R{*}E_C + C_U$ circularity indicator: end-of-use

Table 1. Parameters and metrics for CI calculation dependent on use-cycle phase, based on[28, 29]

Finally, the overall CI of a product is calculated from the linear flow index (LFI) and utility factor (F(X)), as defined below:

$$F(X) = 0.9/CI_{use}$$

$$LFI = (V+W) / (2M + (W_F - W_C)/2)$$

$$CI_{total} = 1\text{-}LFI * F(X)$$

Key to constructing complex models is the ability to break a building down into a hierarchy of architectural components, each of which might itself be divided into smaller components. These components are referred to as products. Computing metrics for compound products follows the general rule of mass-weighted sum:

$$\sum (CI_{sub\text{-}product} * M_{sub\text{-}product}) / M_{product}$$

METHODS AND COMPONENTS

Rhino*Circular* consists of several components, divided into categories of material, product, and analysis. Figure 1 depicts the user interface of Rhinoceros3D (left) and Rhino*Circular* in Grasshopper (right). Results are displayed directly in the modelling environment for easy reference within the design workflow, while visual scripting of components is done within Grasshopper.

Materials: A standard workflow begins with the selection of materials; this can be accomplished through the "Load Material" component, which displays a list encompassing those materials from the selected database and which is searchable by class of material (wood, stone, plastic, textile, organic, ceramic, and metal). This can be fed into any of the product components. A toggleable parameter of the "Load Material" component triggers an automatic download of the latest dataset from one of a selection of sources including Madaster, ensuring this data remains up-to-date and tied into an enterprise-level repository. Alternatively, one can use the "Custom Material" component to either tweak certain data points of a catalogue material, as for instance if one were to use the density and lifetime estimates of a stock material but provide figures for efficiency of recycling that were more representative of their locality; or to create a new material from scratch using outside data, as for instance if one were to use a building product from a specific supplier's catalogue that provided such information. Given enough information, the "Custom Material" component will calculate remaining values automatically, sparing the need to explicitly enumerate all of the relevant fields.

Product: The second stage of a typical workflow would begin by assigning these materials to components of the 3D building geometry, called products. This 3D model can be explicitly referenced from geometry in the standard Rhinoceros3D editing window, or can be parametrically generated from within Grasshopper, leveraging the flexibility and power of this node-based scripting tool. Products can represent anything from a door knob to an I-beam to an entire façade system, but begin as an object of a single material. These initial products contain information about the referenced geometry, its volume and density (and hence mass), and the material assigned to it. In addition to the product object itself, these components also output the CI values for the product in the construction, use, and end-of-use phases, and overall.

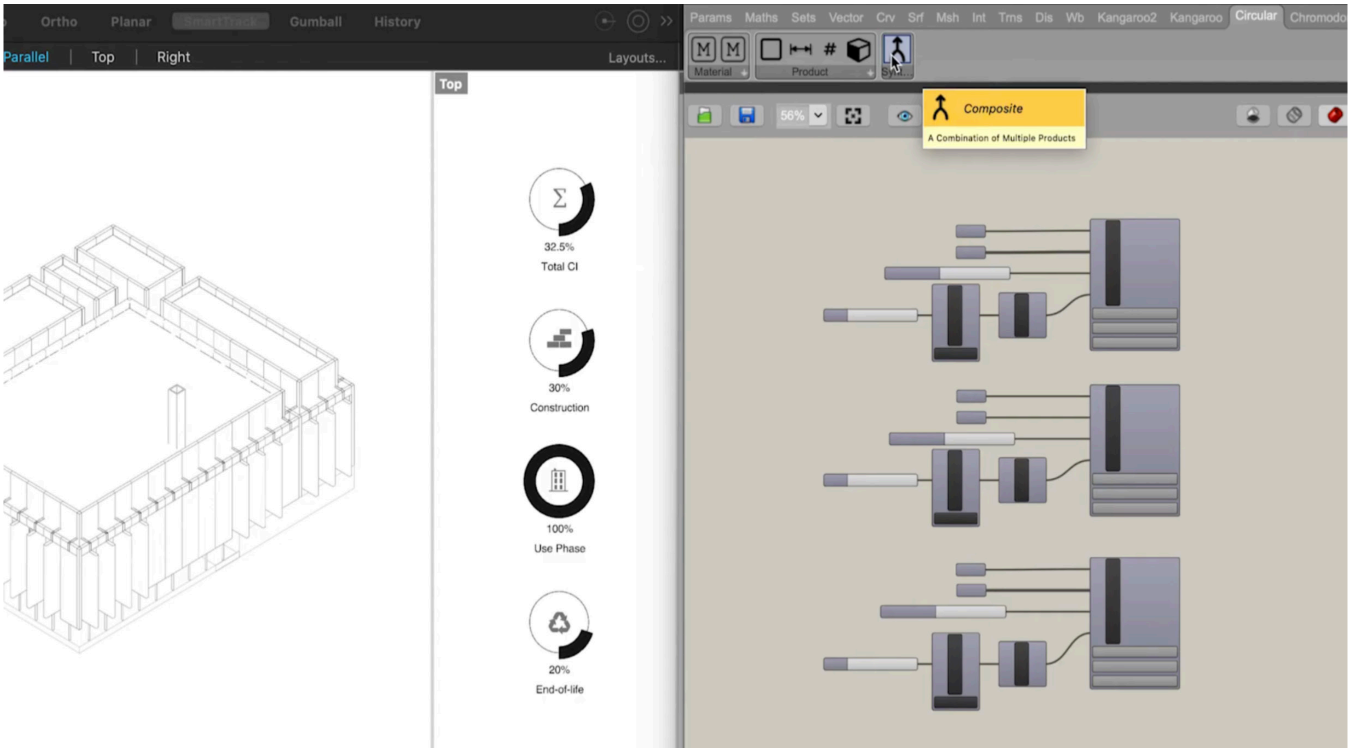

Figure 1. Rhino*Circular* user interface in Rhinoceros3D and Grasshopper. Circular Construction Lab, Cornell University.

This base product can be enumerated in one of four ways, each represented by its own constructor component: length, area, volume, or quantity. Length-based or linear products can reference curve geometry and must provide the cross-sectional area in order to calculate volume, making it easy, for instance, to iterate through different gauges of rope or wire within a parametric design workflow while working with easy-to-manipulate curve geometry. Area-based products can reference surfaces or meshes and must provide a thickness. Volume-based products can reference solid geometry, either BReps (Nurbs boundary representations) or meshes, from which volume is calculated directly. Lastly, for products that do not fit in these categories, or which have no explicit 3D geometry associated with them, the quantity component allows manual entry of the volume and enables one to group large numbers of similar products as would be useful for items like nails, studs, and screws.

Importantly, these components display three clickable buttons labeled "Inaccessible," "Fixed in place," and "Nonstandardized." Toggling the buttons changes them to read "Accessible," "Disassemblable," and "Standardized." If any of the buttons are left untoggled, the product is considered part of the linear economy and therefore the end-of-use CI value will default to 0. It is expected that these must be toggled each time; this is a deliberate pedagogical choice to highlight the question of reversible joinery so that the user is consciously aware of its effect on the overall circularity of a building.

The four base product types are the atomic units of a building circularity model, which can be viewed as a tree in which each tier represents a relevant level of organization within the building, as displayed in Figure 2. In each successive tier products from the previous tier are merged using the "Composite" component, which takes any number of products as input and produces a single, combined product whose CI values are taken as the weighted sum by mass of those of the inputs. Not necessarily a unidirectionally-branching tree, the hierarchy can contain multiple organizations at the same tier (for instance, grouping products by supplier, or by building layer); however, to avoid overcounting, an error is generated if the same geometry is merged with itself downstream. The final merging into a single product represents the building as a whole, giving the total values for all CIs.

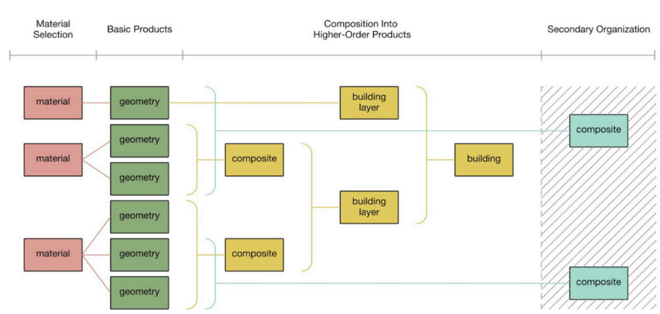

Figure 2. Organization tree of building circularity model within Rhino*Circular*. Circular Construction Lab, Cornell University

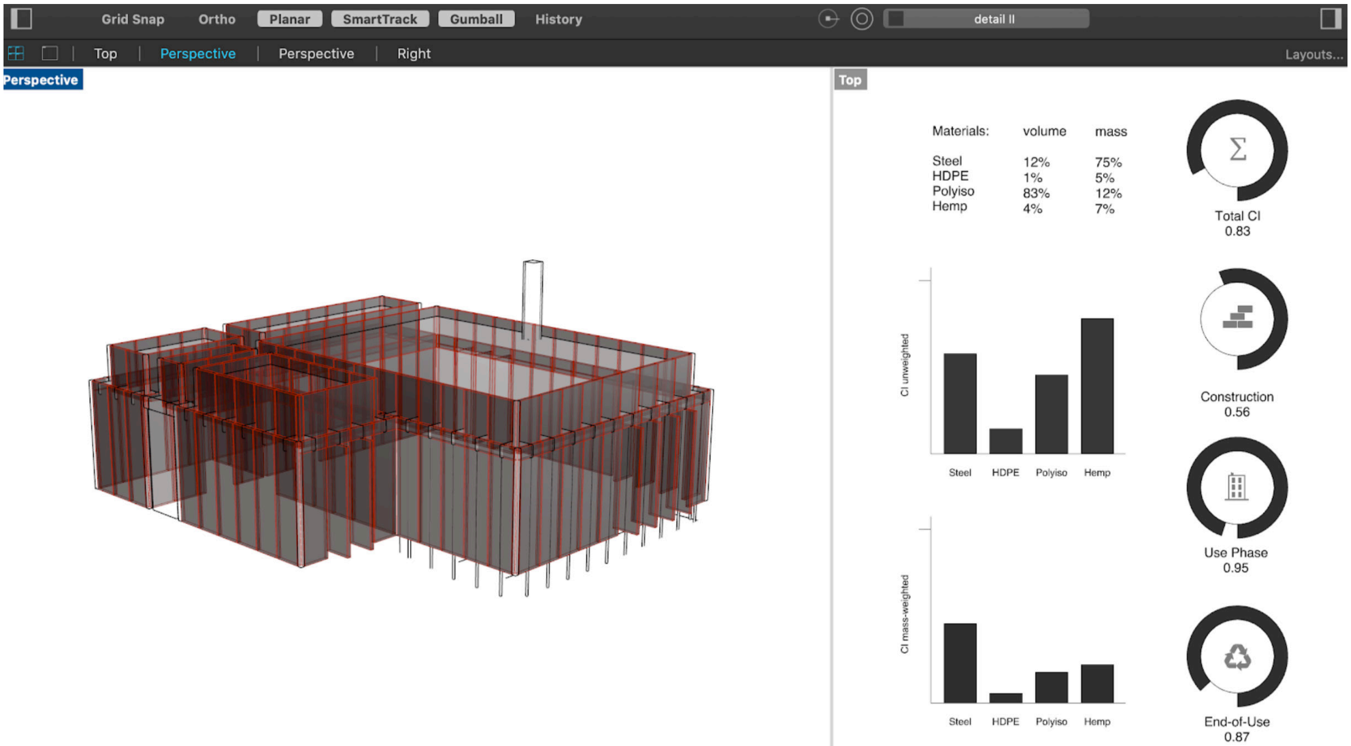

Figure 3. Rhino*Circular* displays calculation results directly within the modelling environment. Circular Construction Lab, Cornell University.

Analysis: A subset of components are specifically concerned with the visualization and publishing of the computed metrics. The "Passport" component takes as input a product, typically the composite product representing the entire building, and generates a formatted, printable file displaying a summary of all key metrics. The "Select" component refines a list of products according to an input criterion: a material to match against, a 1D domain of CI values to test for inclusion, or the satisfaction of the three accessibility criteria described above. Each product contains geometry data such that by selecting its component in Grasshopper, the corresponding geometry may be highlighted in the Rhinoceros3D viewport for quick analysis. In combination with the "Select" component, the passing of geometry data upstream also allows for custom workflows such as highlighting geometry with a color gradient according to CI or material type. The "Graph" component displays a bar graph within a widget in the grasshopper canvas. From the menu the user can select which of the calculated metrics to display for the input product. One can additionally select how to organize the x-axis; for example, one could display the use phase CI for each layer in the CAD file, or the mass weighted CI for each material in the construction. The component outputs include the names and values of each column of the bar graph. An example is shown in Figure 3.

LIMITATIONS AND SCOPE

In contrast to existing software applications that document design decisions based on detailed BIM models for the creation of MPs, Rhino*Circular* is developed as an early design tool to support and influence design decisions in the process. This fact naturally results in a lower level of model accuracy and detail which needs to be considered when calculating CI and embodied carbon values. Consequently, the software is running certain automation processes to fill in the blanks when required data points for the calculation are not yet available in the model or reverts to default values from literature. While we do not see this as problematic - the goal of the software is indeed to allow informed decisions within the often still uncertain context of the early design phase, the level of data accuracy at this moment needs to be acknowledged. With increasing model accuracy throughout the stages of the design process, Rhino*Circular* continuously refines its calculations.

All CI tools are currently still limited by the availability of data on material flows especially towards the end-of-use phase of the cycle. Rhino*Circular* aims to mitigate this limitation through compatibility with several sources and interfaces, as well as through the ongoing development of its own dataset in the background. Additionally, material cycle-specific data such as efficiency of recycling or embodied carbon values are highly dependent on the location of the building, as energy mixes in production, transport lengths and local production, construction and recycling conditions determine the calculation of such inputs. Consequently, Rhino*Circular* asks for a user-defined parameter on the location of the building, however, most data bases are not able to interpret or adjust values depending on specific locations (yet).

With live recalculation of CIs during the design process, it becomes possible for the designer to adjust geometry accordingly. However, the potential for interoperability with other early design analysis tools offers even greater potential. For example, one could adjust the span of a load bearing beam and have the cross-section automatically recalculated with a finite element modeling tool such as the Grasshopper plugin "Karamba3D,"[27] then instantly see the impact this has on circularity as the CI is recalculated for the beam's new mass. This seamless workflow however will only be enabled by centralized material databases such as the forthcoming BuildingRepo where material properties related to all manner of design objectives, from circularity to environmental and mechanical performance, can be accessed side-by-side. This contrasts with common practice, wherein separate, specialized databases are leveraged for each simulation tool, which can make it difficult to ensure that data refers to the same material from one tool to another. To this end, Rhino*Circular* has been developed to be as agnostic as possible to the data source, so that it can easily be grafted into more holistic workflows such as the BuildingRepo toolkit in the future.

DISCUSSION AND OUTLOOK

The implementation of a CE in the built environment through circular construction is technically feasible already today, as the examples of UMAR and other lighthouse constructions around the globe demonstrate. However, its industrial and large-scale application requires fundamental paradigm shifts in design and construction methodologies, economic and social models as well as material production and sourcing. A detailed documentation of the built environment over time represents a precondition for the closing of material cycles in this scenario. Most importantly however, it is a design task to develop circular solutions that implement and reapply existing resources in ways that do not create waste in the process and allow for the continuous use of materials, products and components at their highest utility and value.

This design process requires new tools to support and allow informed decision making and matching of supply and demand within an urban circular system. In this context, Rhino*Circular* provides an integrated tool for predicting the impact of especially early design decisions on the circularity performance of buildings. It allows architects, engineers, and planners to maximize the reusability of buildings from the outset, giving meaningful feedback about circularity even with incomplete information. A 2012 survey reported that 91% of large companies are using BIM, while only 49% of smaller firms reported the same.[28] We may expect similar trends in the adoption of tools for circular building, unless they can be easily and seamlessly integrated in existing and low-cost workflows. Rhino*Circular* aims to be one such solution.

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