‘SMARTIFYING’ CONSTRUCTION FOR CIRCULAR AND ZERO-CARBON BIOBASED BUILDINGS (SmartBioC)

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ABSTRACT

SmartBioC focuses on creating a user-friendly digital tool that allows users to select and specify biobased materials and building components for a modular housing unit based on a set of performance indicators including carbon footprint, thermal performance, cost, social value, health and wellbeing. The ultimate aim of the tool is to speed up the uptake of circular biobased materials to provide zero-carbon, healthy and socially and economically viable solutions for the construction industry. Smart construction integrating the use of digital technologies and modern methods of construction (MMC) has the potential to improve the affordability, efficiency, and sustainability of new and refurbished buildings. Aligned to a circular economic model, opportunities exist to optimise the use, reuse, and disposal of biobased materials within the expanding MMC housing market, thereby improving carbon sequestration and mitigating climate change. Together with industry partners, SmartBioC’s research team is using the UK’s Design Council's Beyond Net Zero Framework of exploring, reframing, creating and catalysing to facilitate a collaborative and iterative process where the end-user is at the centre and determines the final outcome. SmartBioC ‘explores’ data obtained on biobased materials and ‘reframes’ it for alignment with indicators relatable for end-users. A BIM Object library of MMC premanufactured components with alternative biobased material configurations ‘created’ using Autodesk Revit is then exported into gaming platform Unity. Rapid prototyping and testing in Unity allow distribution of a web-based tool (html) for user feedback and development purposes (catalysing). User-friendly digital tools like SmartBioC give end-users, designers, decision-makers and specifiers, the ability to select circular biobased materials whilst visualising their design in 3D, along with information about the environmental, economic and social impacts of their choices. The adoption by the construction industry of zero-carbon, healthy and socially and economically viable biobased building solutions is imperative if the catastrophic impacts of predicted global warming are to be averted.

KEYWORDS: Biobased Construction, Serious Games, Nature-Based Solutions, Smart construction, Digital Technologies, Circular Economy, Life Cycle Assessment, Modern Methods of Construction

INTRODUCTION

Arguments based on sustainability exist in favour of utilising digitisation in construction globally and locally (HM Government, 2020; Thelen, Zijlstra and Zandbergen, 2021). In the UK, the Ministry of Housing, Communities & Local Government (MHCLG, 2019) and the Construction Leadership Council (HM Government, 2018) emphasise the use of digital technologies and industrialised manufacturing as the key to unlocking current competitiveness and sustainability issues in the industry. Digital technologies can accelerate the transition of the construction industry, as outlined by the UK Government’s Construction Strategy 2025, into a 50% less greenhouse gasses polluting industry, with a 50% increase on output speed and 33% cheaper (DBIS, 2013). Conversely, decarbonisation and climate change mitigation targets for the global construction industry, can significantly benefit from the mainstream use of biobased building materials within a circular economy approach. The UK Green Building Council (UKGBC) 2030’s sector ambition statement sets biobased solutions in all building and infrastructure as a priority for reducing both GHG emissions and resource depletion caused by the industry (UKGBC, 2019). Therefore, the selection and/or development and implementation of digital technologies that can, swiftly enable the uptake of circular biobased materials in the construction industry becomes paramount.

Biobased building materials - whether plant or animal based -, are organic and renewable alternatives to man-made (technical materials such as steel and plastic) that sequester carbon during growth and that, depending on their transformation process – can result on a zero or negative carbon balance. Biobased materials such as natural fibres, wool and bio-adhesives can also offer a series of health, wellbeing and environmental benefits. However, at present, biobased materials (a.k.a. biogenic) and sustainable construction and/or green building technologies face several technical, commercial and social barriers, which hinder their rapid and cost-effective uptake in construction applications. Chan *et al.*, (2017) appropriately group the following factors as interconnected barriers to the adoption of 'green building' technologies: 1) Stakeholders' reluctance to change; 2) Limited knowledge, information and awareness; 3) Higher cost compared to conventional technologies; 4) Market and financial constraints; and 5) Technological risk and obstacles. These five broad categories encompass similar barriers outlined by several authors surveying stakeholders across the global built-environment and reviewing the literature in the topic. Darko *et al.*, (2017), Wong and Voon (2020) survey construction experts in the US and Malaysia, whilst Li *et al.*, (2018) and Gan *et al.*, (2015) include owners, end-users and other organisations in China and discuss influential factors in sustainable construction's decisions. Systematic and bibliometric reviews by Darko and Chan (2017) and Det Udomsap and Hallinger (2020), respectively, provide an overview of these barriers across the literature.

The five factors identified by Chan *et al.*, (2017) depict interconnected and at times 'wicked issues' (Goel, 2019) surrounding sustainable construction which are experienced across the supply chain and that respond to broader global constraints. For instance, in terms of cost (2), market and financial aspects (4), biobased building materials are subjected to an 'economy of scale's' focus in the current global economic model. This model understandably prioritises manufactured and financial value (*e.g.,* highest output at the lowest cost) over the natural, human and social value of activities and output of the construction industry and beyond (*e.g.,* knowledge, training, biodiversity gain, human health and local impact). This long-established 'linear economy' model influences a 'take-use-dispose' approach, instigates monoculture and biodiversity loss, and creates social and economic inequalities worldwide. A systemic shift in the construction industry is therefore needed to address the 'wicked issues' facing sustainable construction. Campbell, Hairstans and Jones (2020) argue that a shift to the 'five capitals' model by Porritt (2012) including natural, human and social value, not only manufactured and financial value, can increase sustainability in modern methods of construction (MMC) *i.e.* offsite manufacturing (OSM). Particularly, in terms of fostering natural capital in construction, the authors highlight the current role of timber along with the future potential of other new biobased materials such as hemp, bamboo, straw and mycelium. a) Natural capital refers to the environmental sustainability and includes all resources (e.g., renewable and non-renewable) that are required for any building. b) Human capital measures all benefits to individuals including their physical and mental health and wellbeing, knowledge, skills, motivation, recreation, etc. c) Social capital: indicates the building's contribution to society, communities, family, businesses, culture and to government institutions, schools and networks, etc. d) Manufactured capital evaluates the goods, facilities, infrastructure & technologies required in construction to 'build buildings'. Finally, e) Financial capital measures the financial & economic value of the building choices.

The Alliance for Sustainable Building Products (ASBP) confirms the recent growth in the use of biobased materials in construction, as well as their painstakingly slow adoption (House of Commons EAC, 2022). Therefore, wholistic, systemic and easy to deploy and use solutions are imperative to generate the 'shift' in the construction industry. Innovative solutions to the built environment challenges that integrate new digital technologies could encourage the uptake of biobased materials in the construction industry within a circular economy framework (rather than a linear-economy model). Initiatives in the field, targeted at overcoming such challenges include the EU funded H2020 Building as Material Banks (BAMB) project, which is developing a *'Materials Passports Platform'* and a web-based Circular Building Assessment

(CBA) tool, both aimed at maintaining the value of building materials throughout the building's life from design, construction, and management through to operations, refurbishing and dismantling (Honic, Kovacic and Rechberger, 2019). These types of initiatives are complex and require gathering and analysis of sizeable amounts of material-based data along with the integration of different concepts and metrics to capture the natural, human, social, manufacturing and financial impacts of biobased building products. Transparent information and user-friendliness of digital platforms that appeal to a new generation of digitally savvy building users and stakeholders become fundamental to tackle barriers for the adoption of biobased building materials. In particular, regarding the 'reluctance to change' (1) and the perceived limited knowledge, information and awareness of sustainable building alternatives (2). Kempeneer, Peeters and Compernolle (2021) remark that twenty-first century buildings users are better informed, globally connected and seek a series of environmental and social values (capitals) in the products and services they consume.

Therefore, data science and digital engineering technologies can play a significant role on the delivery transparent and comprehensive information systems in the current climate emergency. SmartBioC explores how digital imaging technologies, data science, building information modelling (BIM) and serious games tools can accelerate the uptake of circular biobased materials to provide zero-carbon and socially and economically viable solutions for the construction industry. These tools are explored as a way of encouraging decision makers (*e.g.*, architects, contractors and developers) and end-users to adopt biobased building materials. Alongside the integration of material information databases (*e.g.,* data on LCA, thermal performance and strength), the visualisation aspect and the interactivity of a digital platform are key to provide a biobased building decision tool that is fit for the future. This 'smart' platform can help users and the industry make informed decisions on biobased building material choices with the ability to increase human, social and natural capital, whilst maintaining manufactured and financial capital. This paper presents the conceptual framework and the methods adopted for 'smartifying' construction for circular and zero-carbon biobased buildings (SmartBioC). Early concept modelling using Autodesk Revit and the workflow developed are also presented.

INTEGRATING DIGITAL TECHNOLOGIES FOR SMART BIOBASED CONSTRUCTION (SmartBioC)

The development of the digital tool(s) at the core of SmartBioC is aligned to the Beyond Net Zero's systematic design approach by the Design Council (2018) which supports action towards the achievement of sustainability goals and climate commitments. As such, SmartBioC's design process comprises four stages: exploring, reframing, creating and catalysing, which entail the mining of data (explore) that is 'decodified' (reframe) through a smart visualisation (create) strategy enabling user interaction (catalyse).

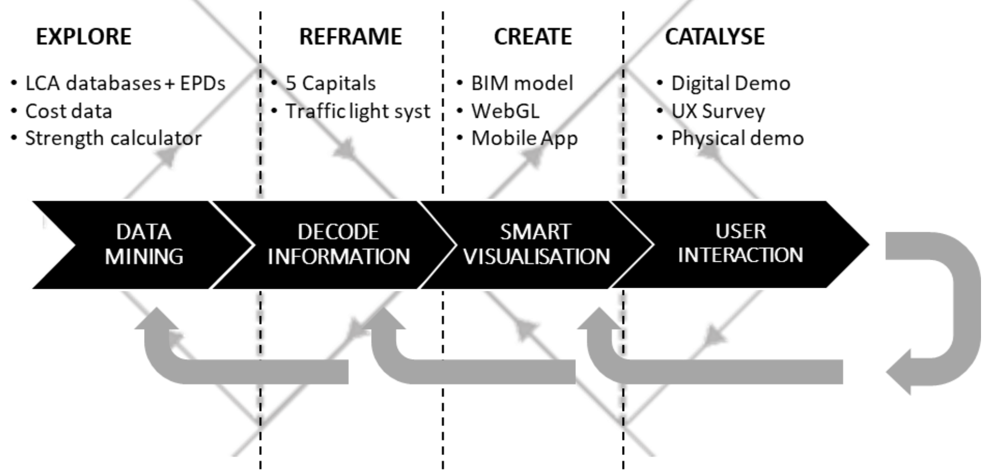

Figure 1. SmartBioC's methodology using Beyond Net Zero's approach (Design Council, 2018)

Figure 1 illustrates these four stages of the framework applied to the project and their continuous iteration, whilst Figure 2 illustrates the workflow generated with the digital interfaces for the development of the SmartBioC tool(s).

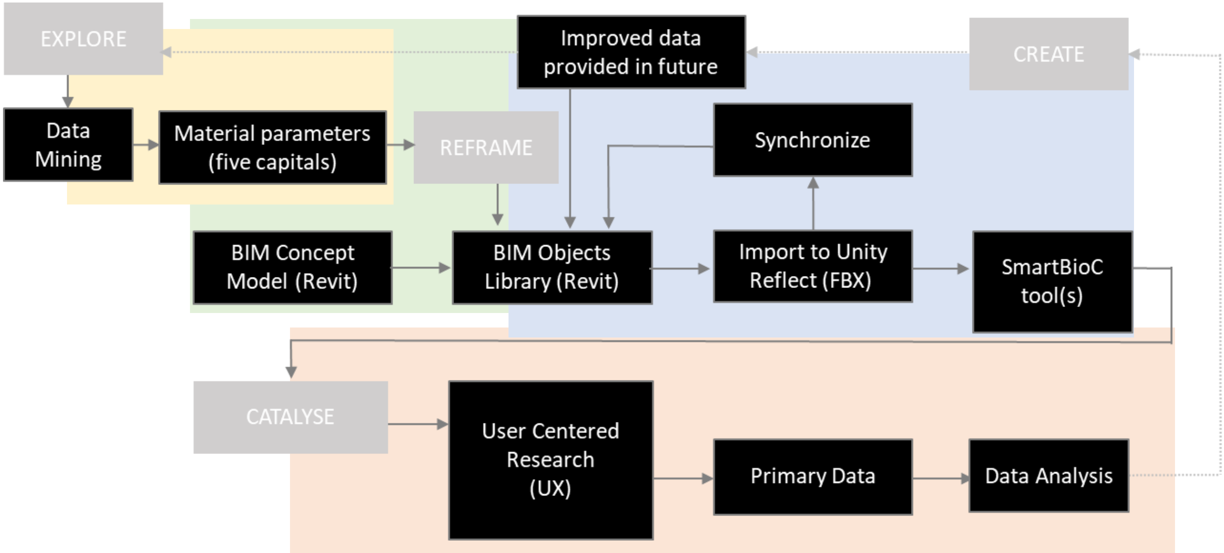

Figure 2. SmartBioC's workflow with digital interfaces.

EXPLORE - Data mining.

Initial data parameters on physical and mechanical properties, thermal and VOC emissions, along with information on price and CO_2 have been sourced for a series of biobased materials directly from suppliers and retailers in the UK (e.g., estimated price) and from Environmental Product Declarations (EPDs). Some of this data is presented in Table 1 for structural timber products such as CLT, LVL and Glulam, timber-bamboo hybrids (TimBam) and for insulation materials made from straw, hemp and agricultural fibre (ECOboard).

Table 1. Biobased material parameters

Product	Density kg/m^3	Strength N/mm^2	MOE ǁ (E_0) N/mm^2	λ W/mK	U value	CO_2 ($kgCO_2e$)	VOC emissions	Est. Price £
TimBam5[r] **Amphibia BASE**	581	77.5 (B)	21,740	0.13	0.295	0.19 /kg - 109.5 /m^3	Formaldehyde free PUR	£ 825[r] per m^3
CLT **KLH**	480	24 (B)	12,000	0.12	0.375[f]	0.25 /kg[s] - 120 /m^3	VOC free & formaldehyde free PUR (EN 15425)	£ 715[o] per m^3
Glulam (GL24h) **Buckland Timber**	420	24 (B)	11,500	0.13	0.295[h]	0.28 /kg[s] - 134.4 /m^3	Formaldehyde emission class E1 in accordance with EN 14080:2013	£ 2,400[p] per m^3
Beam BauBuche GL75 Pollmeier	730	75 (B)	16,800	0.17	0.566[i]	[1,468 /m^3] biogenic only	VOC free & formaldehyde free PUR (EN 15425)	£ 3,725[q] per m^3
ECOBoard Softboard **ECOBOARD Int b.v**	489	7.8 (B)	1,041.90	0.065	1.626[j]	0.98 /kg	No formaldehyde or other VOCs (MDI polyurethane)	-
Hemp Blocks **The Hemp Block Company**	330	0.9 (C)	-	0.07	0.22	100 /m^3	No VOC reported	£10.77* / block
Straw Bale Panels EcoCocon	110[c]	-	-	0.645	0.123[l] 0.145[m]	2.48 /m^2	No VOC reported	-

Key nomenclature: B (bending); C (compression); ǁ (parallel to grain); ⊥ (perpendicular); λ: Lambda (thermal conductivity); Rs-F (Resistance to Fire); R-F (Reaction to fire); ETA (European Technical Approval); REI marking identifies the fire-resistance rating of a structure; * rough pre-pandemic commercial prices.

Other details: a) 28 days; b) 3 months; c) compressed straw; d) fresh mortar; e) dry hardened mortar; f) = 0.320mm/ 0.12=2.667=1/ 2.667; g) = 0.440mm/ 0.13= 3.385= 1/3.385; h) = 0.440mm/ 0.13= 3.385= 1/3.385; i) = 0.3mm/ 0.17= 1.765= 1/ 1.765; j) = 0.040mm/0.065= 0.615= 1/ 0.615; l) with clay and wood fibreboard; m) without; n) = 0.100mm/ 0.30= 0.333= 1/ 0.333; o) calculated from 210mm floor price =£150/m^2; p) Douglas Fir; q) calculated from supplier in Canada; r) calculated values for 2-ply Timber and 3-ply Bamboo laminate; s) revised biogenic factors by ICE database in IStructE carbon guide

REFRAME – Decode information.

The Five Capitals Framework by Porritt (2012) has been used for indexing the data acquired from biobased materials into indicators that can potentially ease their interpretation by users. Overall, these capitals simplify the wealth of data on sustainability and encompass all the UN Sustainable Development Goals (SDGs). Data on the biobased material parameters, metrics and assessment methodologies have been related to these five capitals as shown in Table 2.

Table 2 Metrics and assessment methodologies for capital parameters

Capitals	Metrics	Assessment Methodologies
Natural	kWh/m^2/y and kgCO$_2$e/year	CIBSE TM 54 Evaluating Operational Energy Use of Buildings at Design Stage (2013) *Update 2022*
		Passivhaus PPHP
	kWh/m^2/y and kgCO$_2$e/floor area m^2	RICS Whole Life Carbon Assessment for Built Environment, 2017
	m^3/person/year	England and Wales building regulations water calculator
	increase in new flora or fauna species on site	BREEAM 2018 bio-diversity credits
		Urban Green Factor, London Plan.
Human	m^2 per person	BCO, DfE, HQM
	Response time	Usable Buildings Trust
	CO2, CO, NOX, PM25, PM10, Mould, VOC	CIBSE TM40, WELL v2
	Degrees centigrade	CIBSE
	Reverberation time and Noise Rating NR appropriate to use	
	Open window within 7m	BREEAM, WELL
	Biophilia - contact to views, places, plants, natural materials	
		Good Homes Alliance overheating guidance
Social	kgCO$_2$ e per km per person per annum	BREEAM 2018 Transport Credits.
	Various metrics	WELL Building Standard v2 Preconditions, 2019.
		RIBA Social Value Toolkit, 2019.
Financial	£/m^2, m^3	CMS Global Consistency in Presenting Construction and Other Life Cycle Costs, 2019.
Manufactured	Density (kg/m3); Strength & MOE (N/mm2); MC; Service class; Fire resistance; etc	Performance: Physical, mechanical, durability, fire
	λ (W/Mk); U value	Thermal performance
	Circularity	Adaptability, reusability, adaptability
	kgCO$_2$ e per km	Transport

CREATE – Smart Visualisation

Following the gathering and processing of data for individual biobased materials and their indexing against the five capitals, the next step consists of visually showcasing the information for user interaction. This stage follows a two-fold approach with a series of software interfaces. Firstly, BIM Object libraries of three main biobased building components (floors, walls and roofs) are 'created' for a 3D model building using Autodesk Revit (Figure 3).

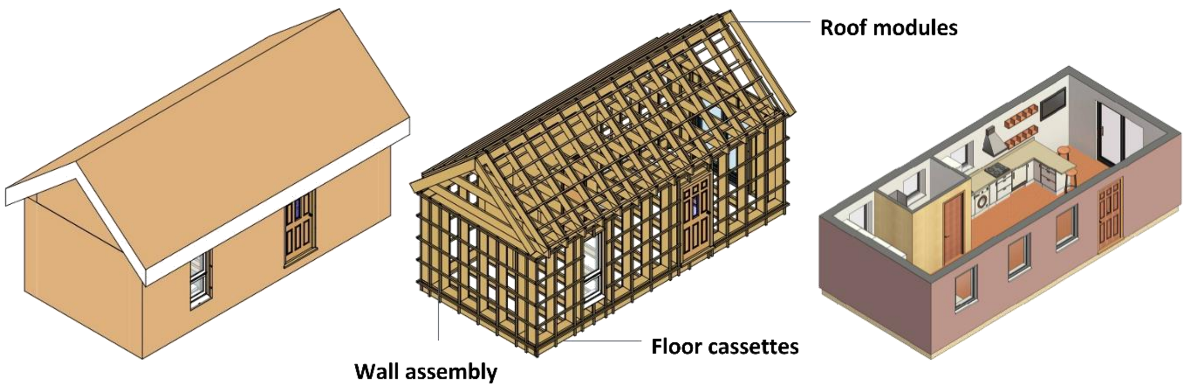

Figure 3. 3D model building views with components

The three biobased building components are conceived for design for manufacture and assembly (DfMA) and for future disassembly, and contain the parameters and metrics defined in the previous stage. Figure 4 displays the floorplan of the model building unit with the wall build-up, which includes the main structural support using TimBam panels (65.75mm), straw bale insulation panels (140mm), agricultural fibre panels (18mm) and internal lining plasterboard made from lime and food crop by-product (12.5mm).

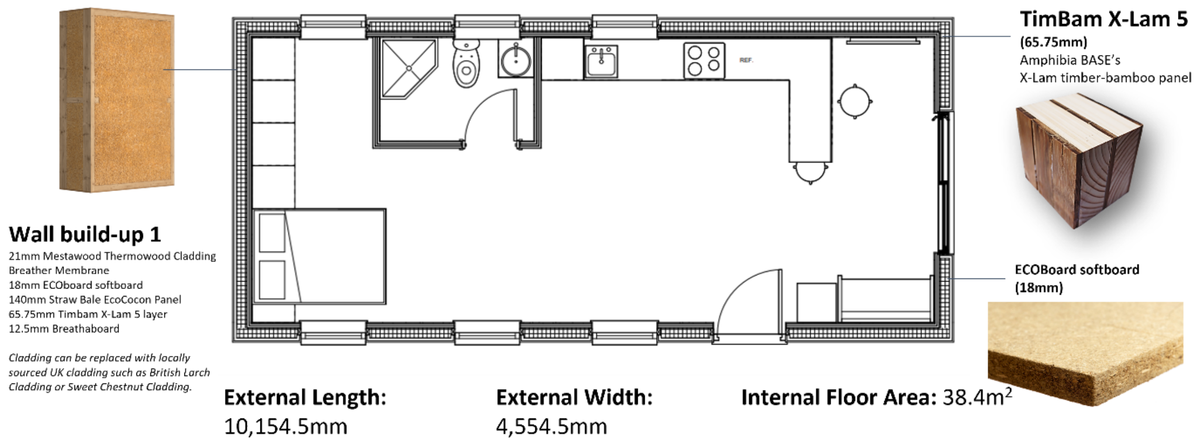

Figure 4. Floorplan of the model building unit with details of the wall build-up

Secondly, the BIM Object libraries are exported into Unity to generate the bulk of the SmartBioC tool. The Unity Reflect plugin allows streaming of data from Revit into Unity. Gaming platform Unity is then used for 'creating' a WebGL 'Builder' and a mobile App 'Viewer' which are purposedly chosen to enable 'easy' distribution and user interaction. In effect, users with access to a computer web-browser can select different building components (BIM Objects) and 'build' their own one-storey design in 3D using the WebGL builder (alike IKEA's online design tool for rooms or kitchens). The 'builder' application displays the five capitals weightings for each building component available using a 'spider' radar chart with one capital per axis (Figure 5). The users are then, free to choose their combination of floor, roof and wall assemblies based on the natural, human, social, manufactured and financial impact weightings (i.e., five capitals) presented to them. The target of this 'serious game' application is for the players (users) to achieve the highest score in the five 'capitals' (green zone), which measure the overall sustainability of their building.

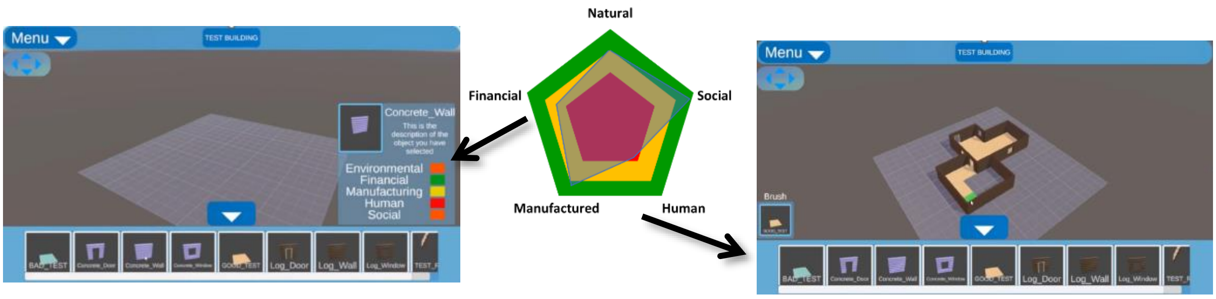

Figure 5. Screenshots of the WebGL builder with the menu of building components available (objects) and the five capitals weighting per object.

Alongside the builder, the accompanying mobile app developed provides an Augmented Reality (AR) 'Viewer' which allows the user to navigate, visualise and interact with the individual components (objects) and the constructions by them created (using the builder). The aim of the combined use of the Builder and the Viewer is to help users better understand the overarching impacts of their building choices and ultimately enable them to make use of biobased building solutions which could have positive impacts on the environment, their health and wellbeing, the communities they live in and the economy.

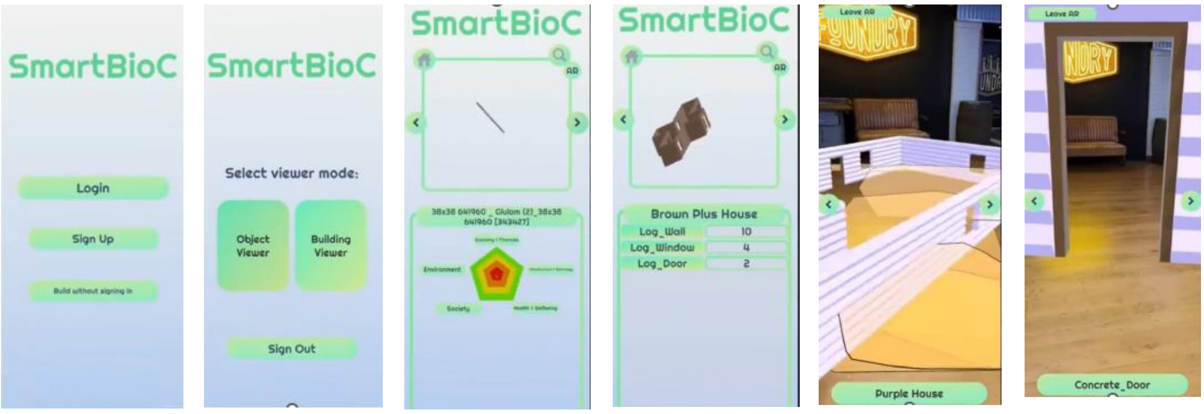

Figure 6. Screenshots of the mobile App 'Viewer' and the 'user journey'. The images from left to right display: 1) logging in into the App; 2)choosing the object or 'building' viewer; 3) visualising the radar chart for the object or building and their attributes (4); 5) placing of the object/building onto a surface; and 6) interacting in AR with the object/building.

CATALYSE – User interaction.

To date the WebGL 'Builder' and the mobile App 'Viewer' are still under development and the 'catalysing' phase involving user interaction has not formally started. In this phase 'user-experience' data will be collected for improving the SmartBioC tool.

CONCLUSIONS

Digital technologies can offer a low-investment solution to tackle recurrent technical, commercial and social barriers, which hinder the rapid and cost-effective uptake of biobased and climate-neutral solutions in construction. Researchers and entrepreneurs developing biobased building solutions are frequently confronted with these barriers. Smart tools like SmartBioC can both help rapidly simulate building alternatives and capture user preferences, whilst educating users on the benefits of adopting zero-carbon, healthy and socially and economically viable biobased building solutions. SmartBioC is an exploratory study into the effectiveness of this 'fairly' low investment digital tools to enable mainstream adoption of biobased building solutions. This digital tool(s) can provide a testbed for biobased solutions with potential users to validate their business case and foster research, development and investment. It is however important to highlight that highly specialised, and nowadays in high demand IT skills, is paramount, along with the analysis of vast amounts of information relating the 'sustainability' of building solutions. For instance, there are dozens of LCA databases and somehow conflicting and/or complex methods of assessment which hinder understanding by end-users and construction professionals. The SmartBioC project observes the need for a shifting of value in the built environment, from a concentrated focus on financial and manufactured 'capitals' to a balanced focus on the environmental, social and human capitals encompassing any building. User testing of the digital tools will assess their potential to unravel the positive impacts that balanced biobased building solutions can have on the environment, human health and wellbeing, society and the economy.

ACKNOWLEDGEMENTS

The authors are grateful to UWE's Vice-Chancellor's Early Career Researcher (VC ECR). Development Awards for the financial support provided to the principal investigator Dr Hector Archila. Amphibia BASE Ltd is grateful to the UK government's Department for Work and Pensions for funding provided through the Kickstart Scheme for two young placement posts contributing to the research.

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